

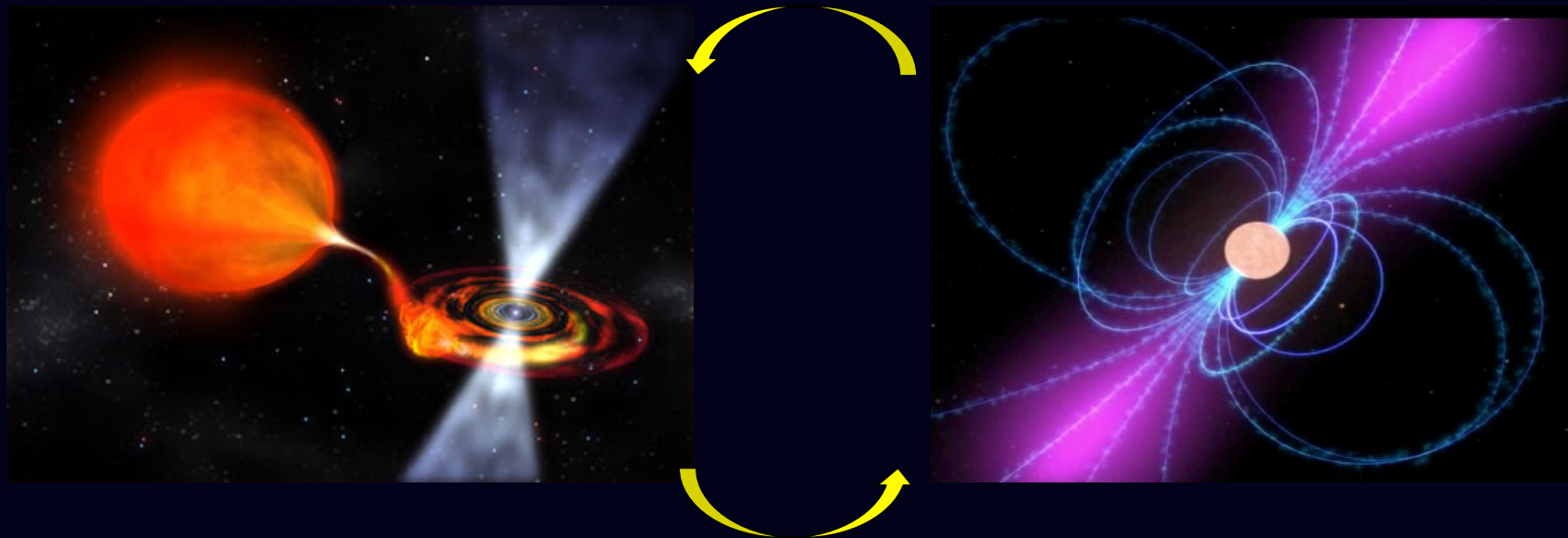


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<i>Title</i>	Transitional Millisecond Pulsar Binaries
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Transitional Millisecond Pulsar Binaries

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(INAF-OA Rome)



“The X-ray Universe 2017” – Rome , 6-9 June 2017

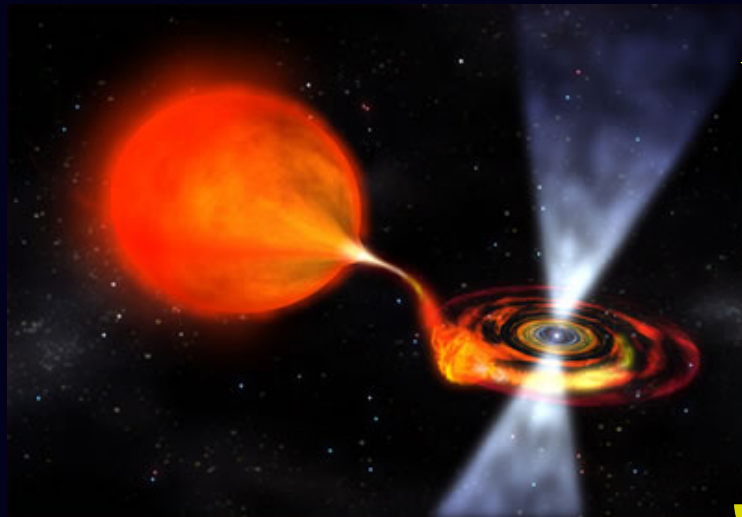
LWASS 2010 : Symposium 15: Athens, July 7-8, 2010

Millisecond Pulsars

AMXPs

Accretion-power **X-ray** ms Pulsars

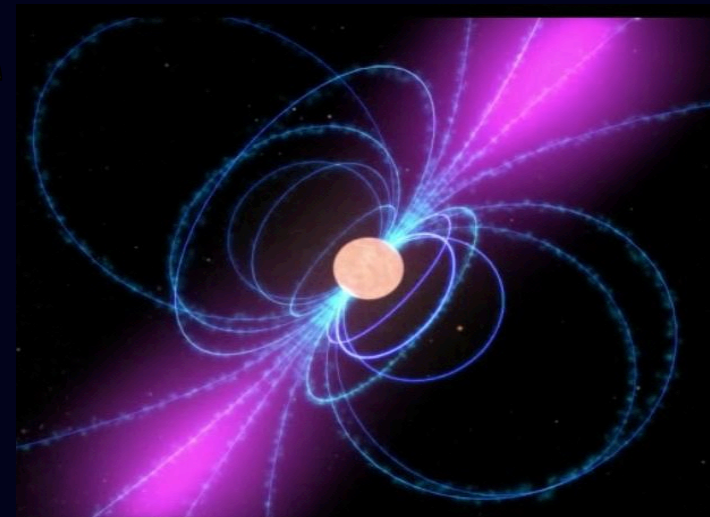
X-ray bright & radio quiet



RMSPs

Rotation-power **radio** ms Pulsars

Radio loud & X-ray faint



?

Fundamental Plane of Pulsars

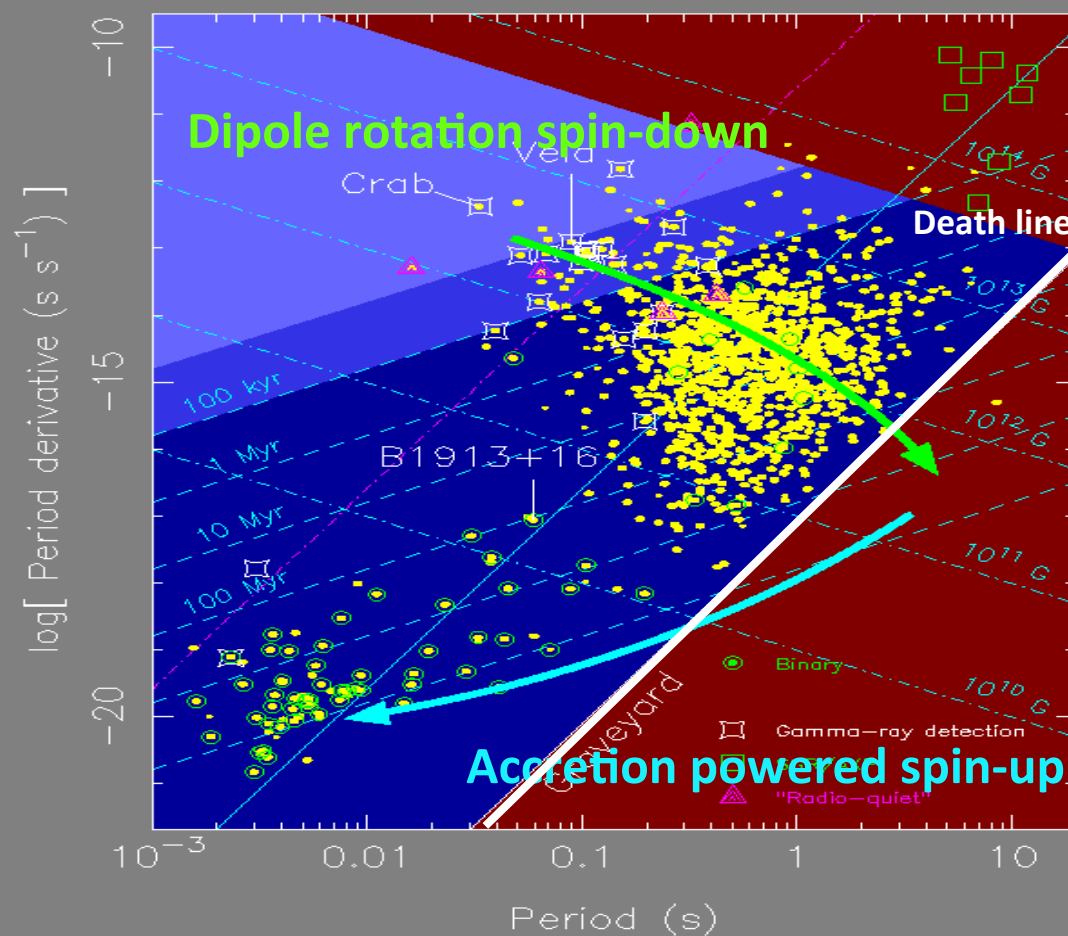
Millisecond pulsars:

- Low fields: $B \approx 10^8 - 10^9 \text{ G}$
- Many in Globular Clusters



Old systems

- Most in found in binaries
- Spin-up due to accretion



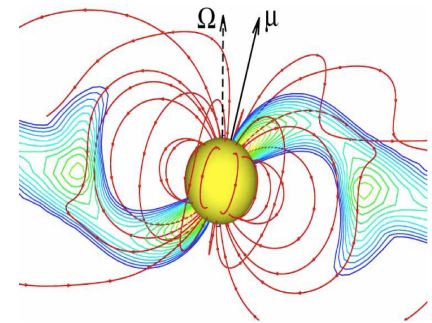
Recycling scenario:

AMXPs believed to be progenitors of RMPS (Baker 1982; Alpar et al. 1982)

What link between LMXBs and radio MSP?

LMXBs hosting AMXPs

- Subclass of LMXBs: 19 systems - $P_{\text{spin}} < 10\text{ms}$; $B \approx 10^8\text{-}10^9\text{G}$ (Patruno & Watts 2012)
- Long quiescence: $L_x \approx 10^{31} - 10^{34} \text{ erg/s}$
- Occasional outbursts: $\Delta T \approx \text{days to yrs}$ $L_x \approx 10^{36} \text{ erg/s}$
- Compact binaries: $P_{\text{orb}} < 1 \text{ d}$
- RLOF Donors: MS, CO/He WD - $M_2 < 0.2 M_{\odot}$
- 10 Nuclear-power MSPs: Type-I bursts - Quasi-coherent Oscillations (Watts 2012)



What link between LMXBs and radio MSP?

Rotation-power ms pulsars (RMSPs)

- ≈ 340 radio MSPs: $P_{\text{spin}} < 30\text{ms}$; $B \approx 10^7\text{-}10^9\text{G}$; $\dot{E}_{\text{spin-down}} \approx 10^{34}\text{-}10^{35}\text{erg/s}$
- ≈ 200 are in compact binaries : $P_{\text{orb}} < 1\text{ d}$
- ≈ 60 show irregular radio eclipses $\rightarrow$ mass loss from ablated donor star:
 - 38 “Black widows” (BW)** - $M_2 < 0.04M_{\odot}$ (degenerate)
 - 22 “Redbacks” (RB)** - $M_2 \approx 0.1\text{-}0.4 M_{\odot}$ (MS) (Roberts 2011,2013)

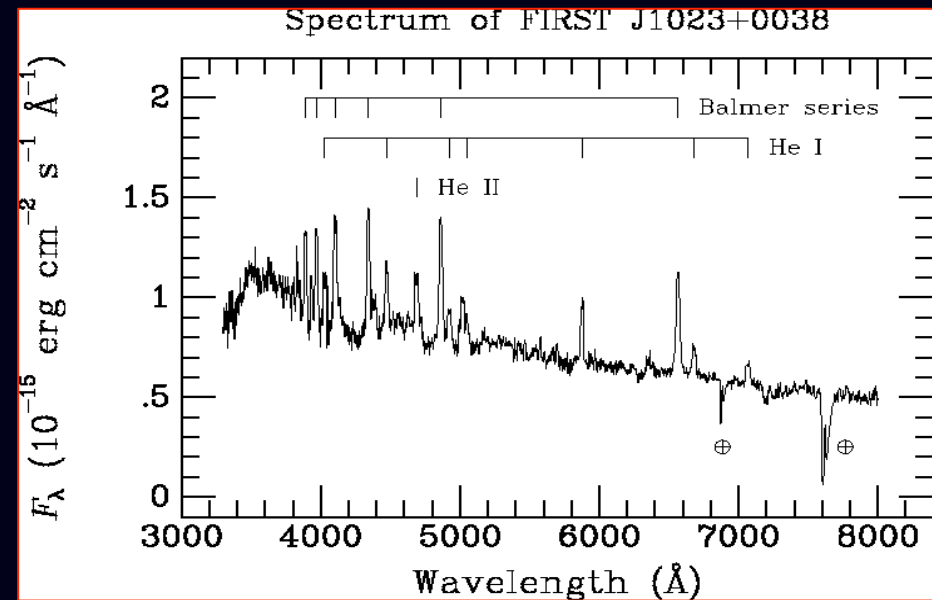
[Listen M. Roberts - BINARY III on Wed. afternoon]
- ≈ 50 detected as Gamma-ray **Fermi-LAT** sources
(Fermi Coll. Science 2009, Pietsch et al Science. 2012, Acero et al. 2015)
- BW believed to descend from RB but not all RB evolve into BW (Benvenuto 2014)

PSRJ 1023+0038: the missing link binary MSP

CV-like optical spectrum!

Optical flickering

Variable radio source



Bond et al. 2002
Szkody et al. 2003

PSRJ 1023+0038: the missing link binary MSP

CV-like spectrum!

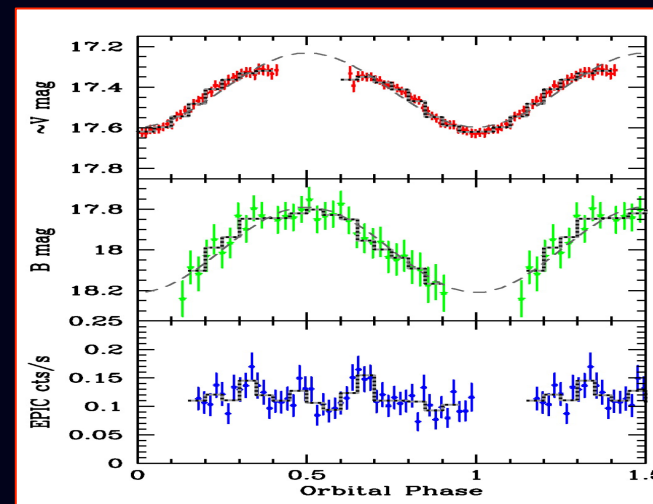
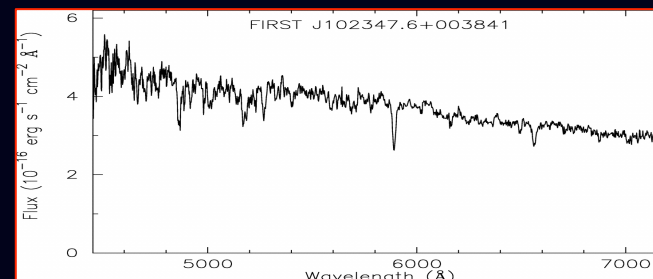
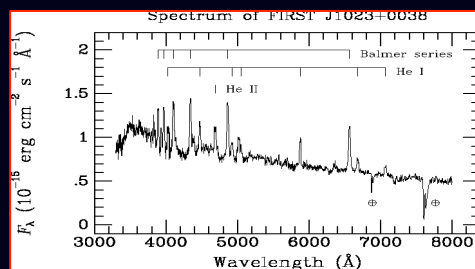
Optical flickering

Variable radio source

No Accretion disc

Optical modulation @4.75h

Variable X-rays



2000

2001

2002

2003

2004

time (yrs)

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&Armstrong2005

PSRJ 1023+0038: the missing link binary MSP

Variable radio source

No Accretion disc

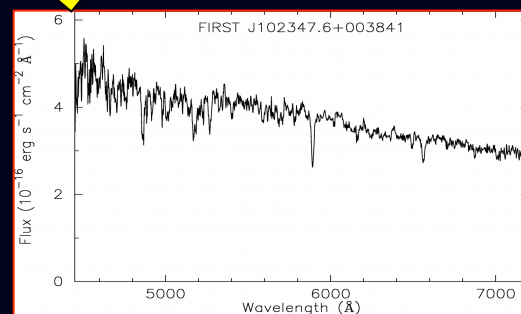
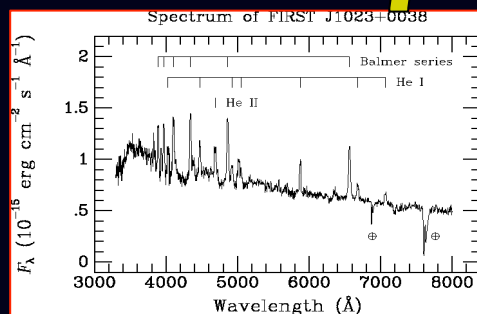
Optical flickering

Optical modulation @4.75h

CV-like spectrum !

Variable X-rays

Change of State



2000

2001

2002

2003

2004

time (yrs)

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&Armstrong2005

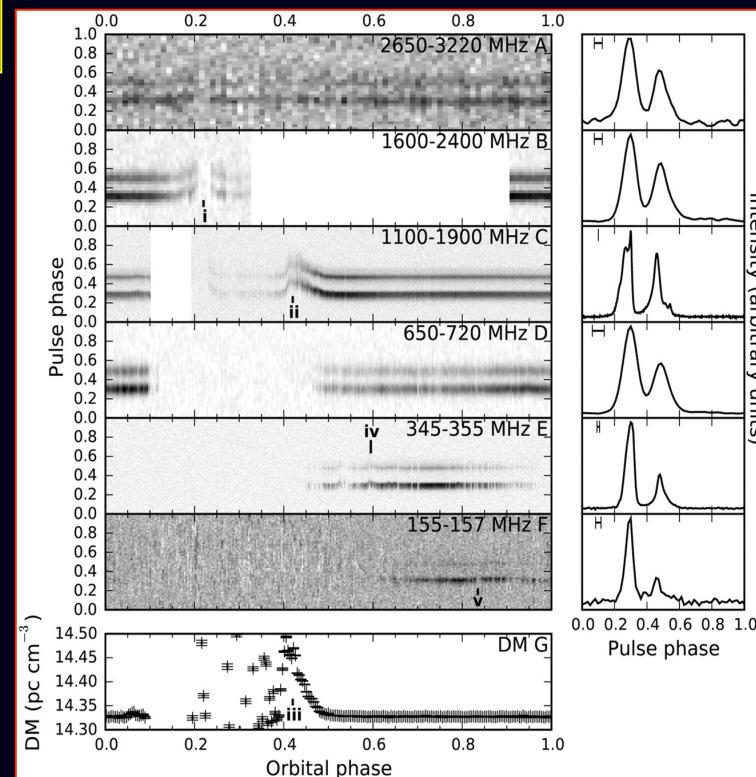
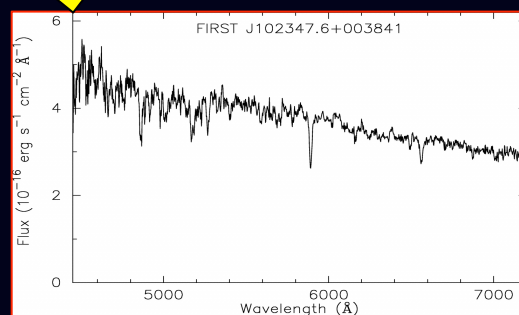
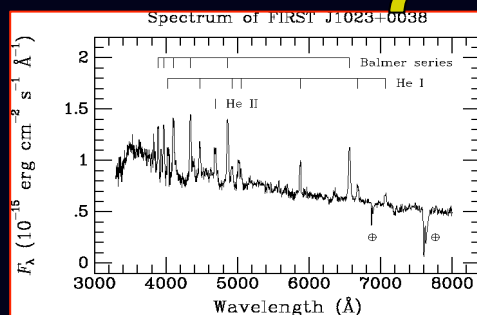
PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @4.75h

Archibald et al. 2009, Science

LMXB

RMSP



2000

2001

2002

2003

2004

2007

2008

time (yrs)

Bond et al. 2002
Szkody et al. 2003

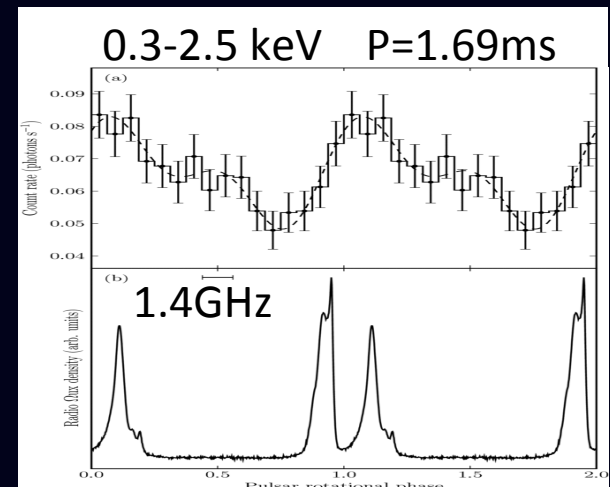
Would et al. 2002;
Homer et al. 2004,
Thorstensen&Halpern2005

PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @4.75h

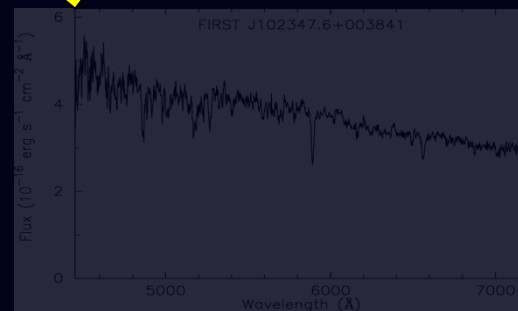
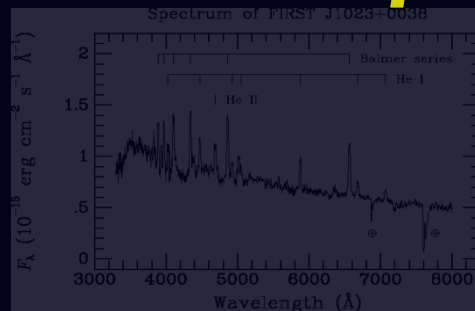
Marginal γ -ray Pulses @ 1.69ms

X-ray Pulses @ 1.69ms



LMXB

RMSP



2000

2001

2002

2003

2004

time (yrs)

Archibald et al. 2010, 2013

PSRJ 1023+0038: the missing link binary MSP

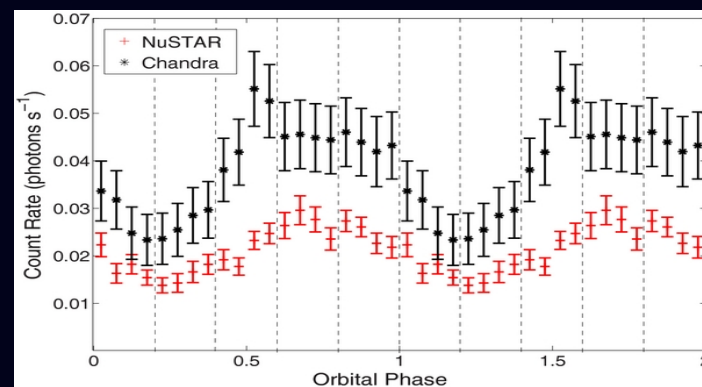
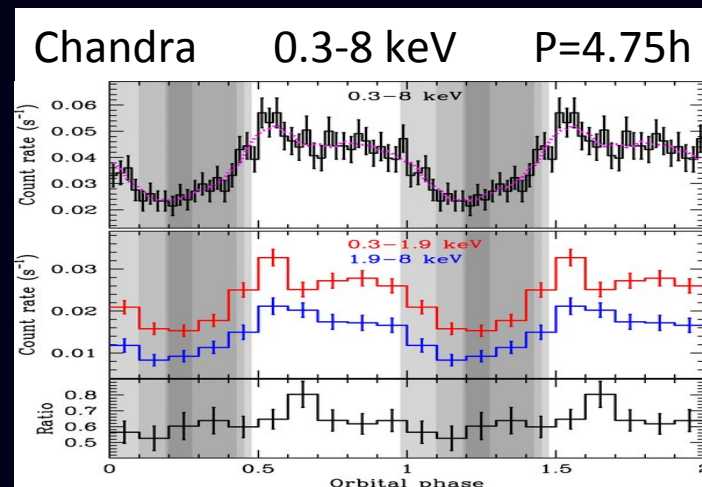
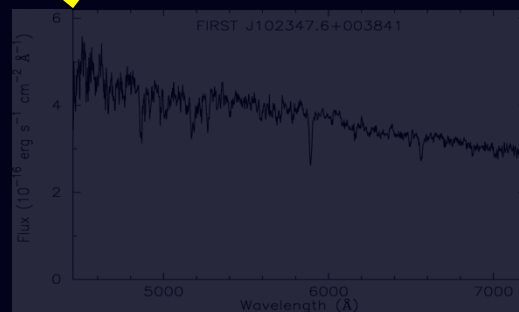
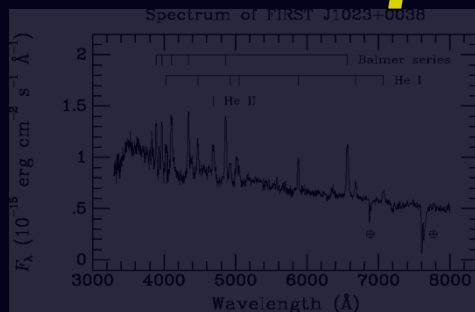
1.69ms Radio Pulsar
Radio Eclipses @4.75h

Marginal γ -ray Pulses @ 1.69ms

X-ray Pulses @ 1.69ms
X-ray modulation @ 4.75h

LMXB

RMSP



2000

2001

2002

2003

2004

Archibald et al. 2010, 2013

Bogdanov et al. 2011

Tendulkar et al. 2014

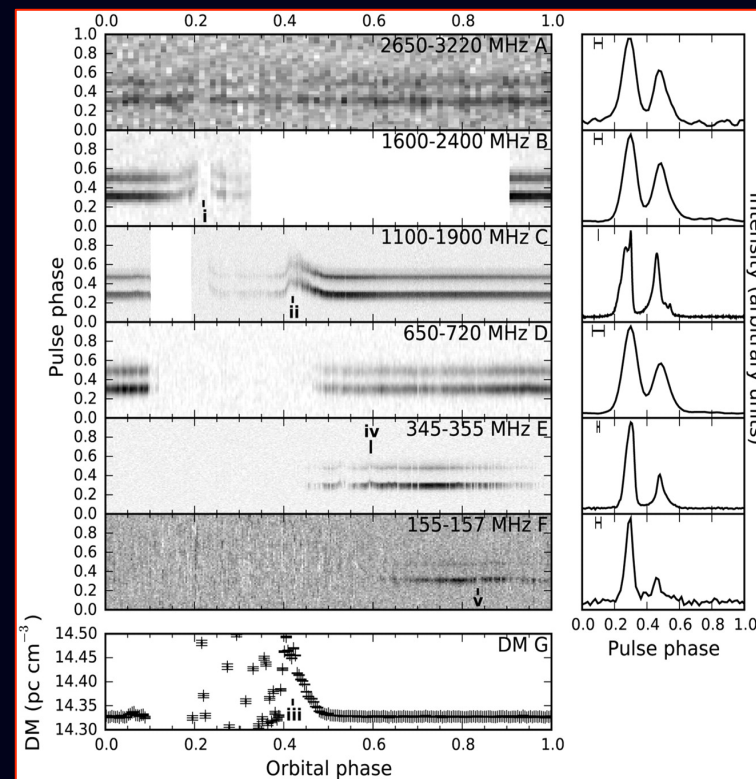
time (yrs)

PSRJ 1023+0038: the missing link binary MSP

1.59ms Radio Pulsar
Period 4.8h
7ms
@ 4.8h
arginal γ -ray Pulse@ 1.7ms

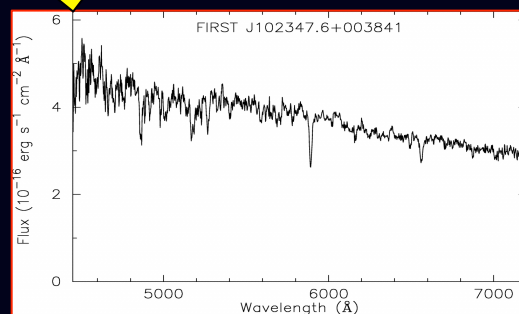
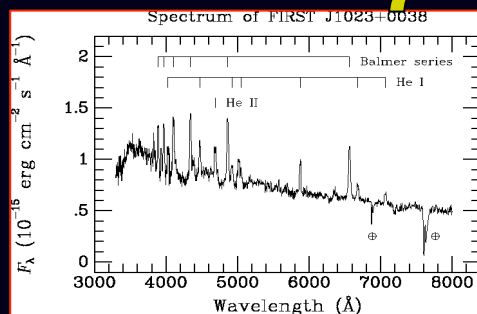
Recycling
Scenario

Archibald et al. 2009, Science



LMXB

RMSP



2000

2001

2002

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2004

2007

2008

time (yrs)

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&2005

Archibald et al. 2010, 2013

IGR J18245-2452: A transient in the GC M28

Papitto et al. 2013, Nature

An AMXP
discovered in outburst

March 28, 2013

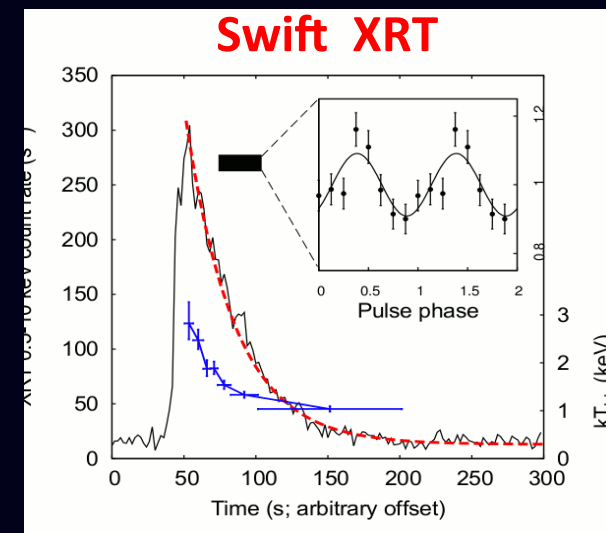
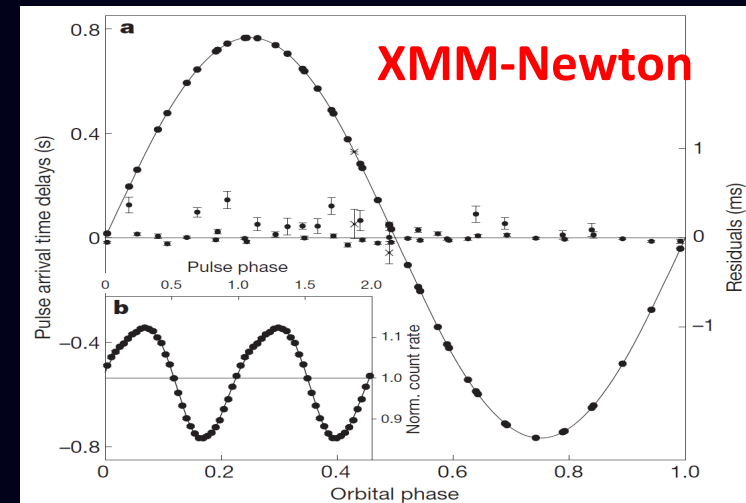
$L_x \approx 1-4 \times 10^{36} \text{ erg/s}$

X-ray Pulses (4-16%) @ 3.9ms

$P_{\text{orb}} = 11.0 \text{ h}$

Thermonuclear Bursts

Peculiar short term X-ray variability



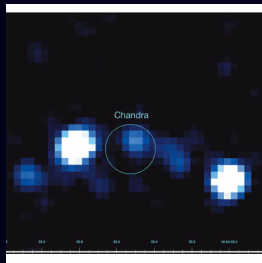
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

Papitto et al. 2013, Nature

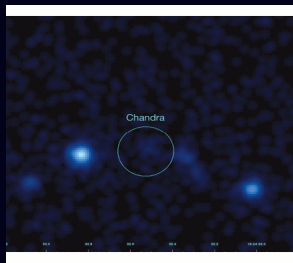
Variable X-ray source

ACIS – S



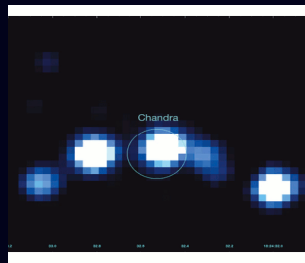
2002

HRC



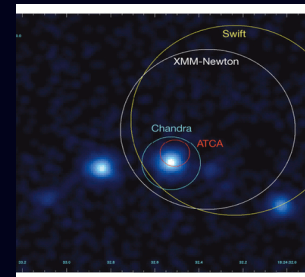
2006

Chandra
ACIS-S



2008

HRC



March-April 2013

time (yrs) →

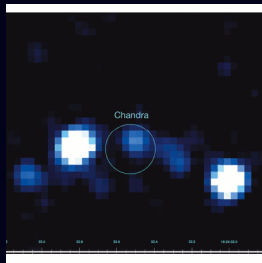
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

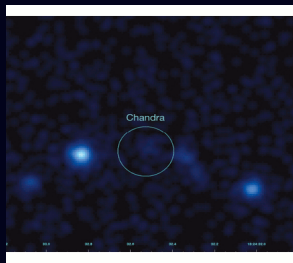
Papitto et al. 2013, Nature

Variable X-ray source

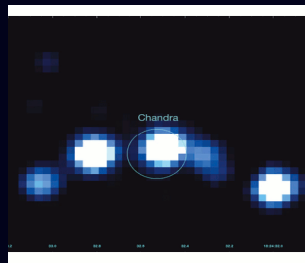
ACIS – S



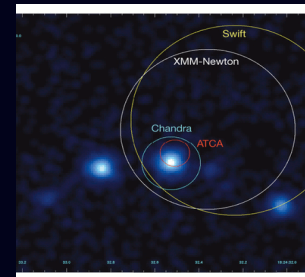
HRC



Chandra
ACIS-S



HRC



2002

2006

2008

2009

March-April 2013

time (yrs)

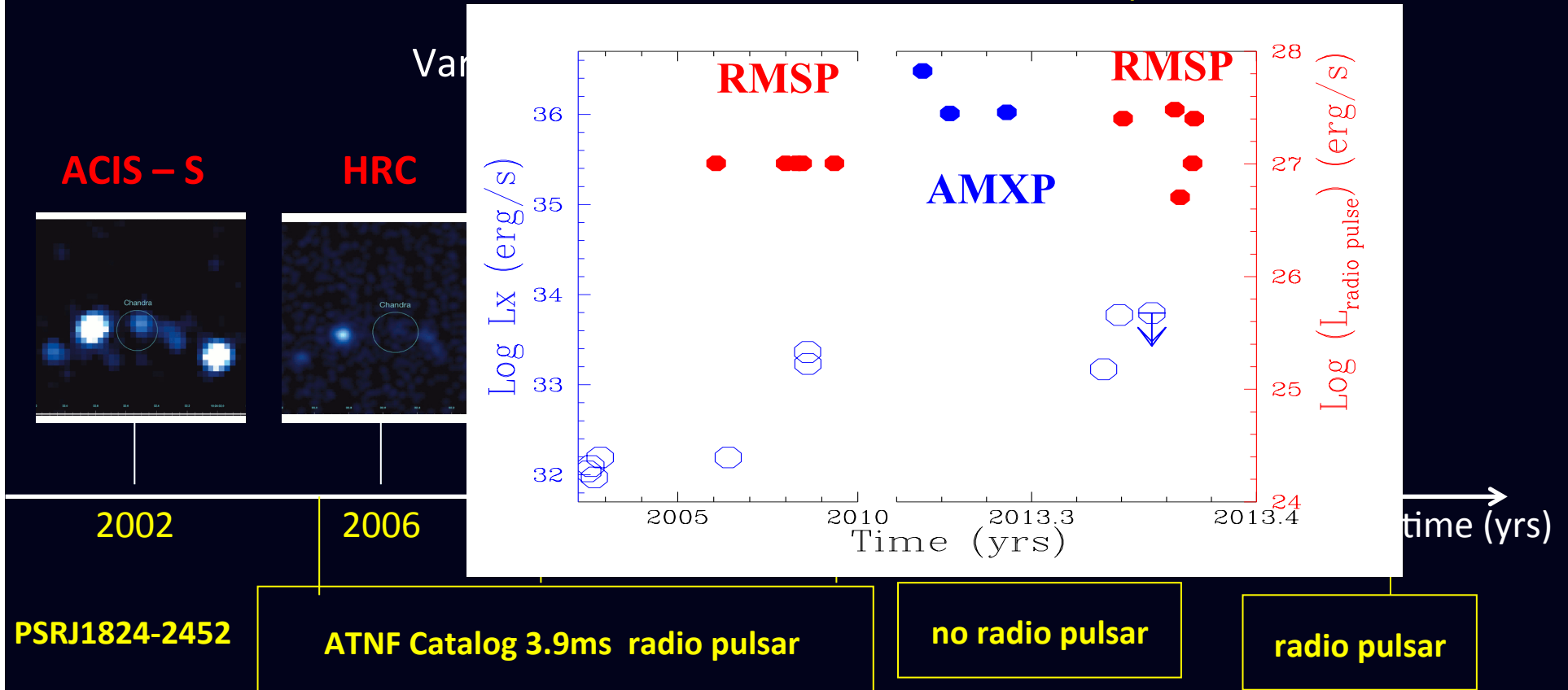
PSRJ1824-2452

ATNF Catalog: 3.9ms radio pulsar

The first swinging MSP binary

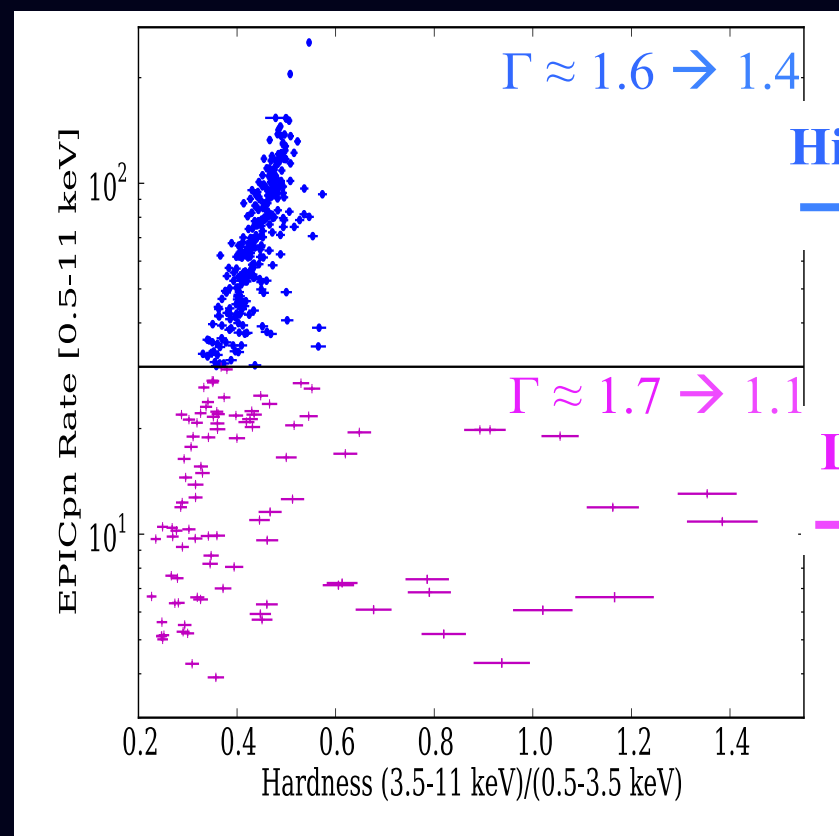
PSRJ1824-2452 / IGR J18245-2452

Papitto et al. 2013, Nature



The first swinging MSP binary

Peculiar X-ray Variability in Outburst



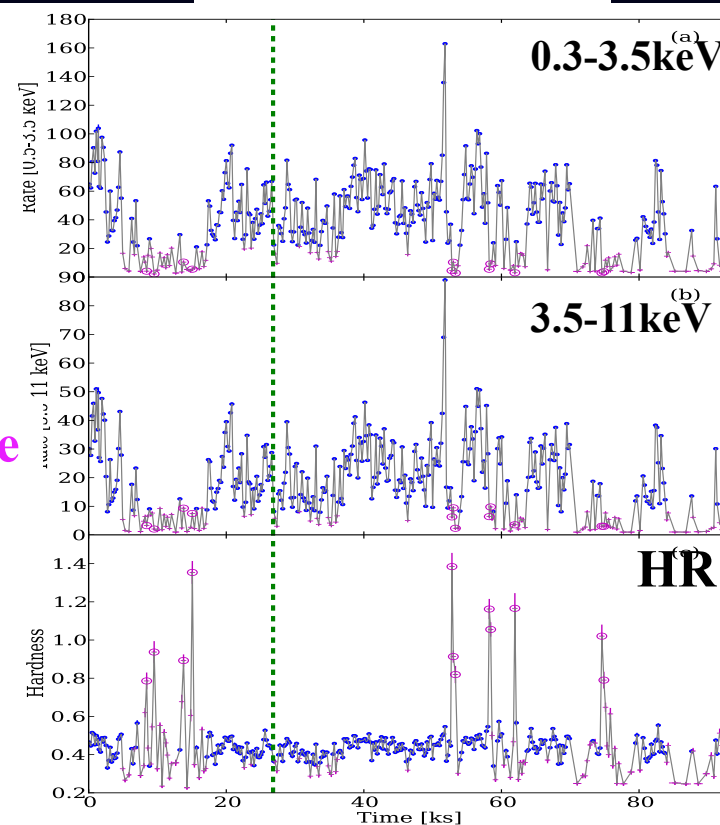
High Mode



Low Mode



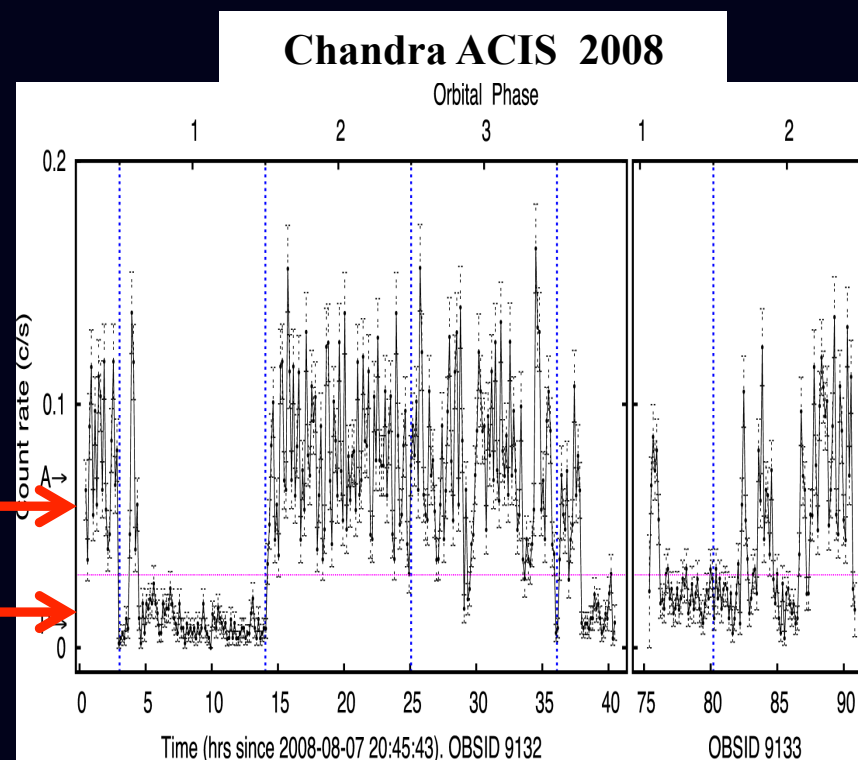
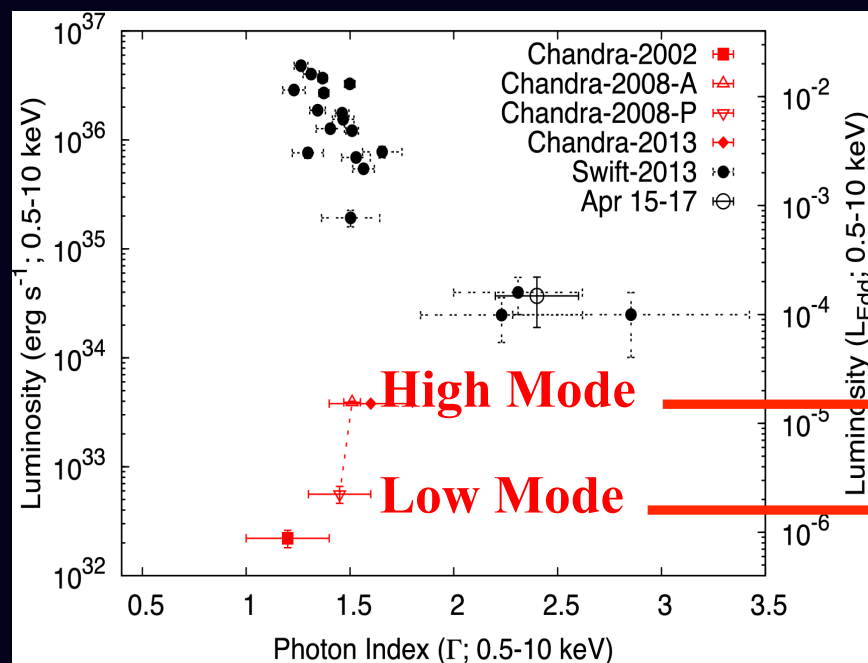
XMM-Newton



Ferrigno et al. 2014

The first swinging MSP binary

Peculiar X-ray Variability also in a sub-luminous state



Mode switching

Accretion $\longleftrightarrow$ Inhibition of accretion

Linares et al. 2014

Papitto et al 2013

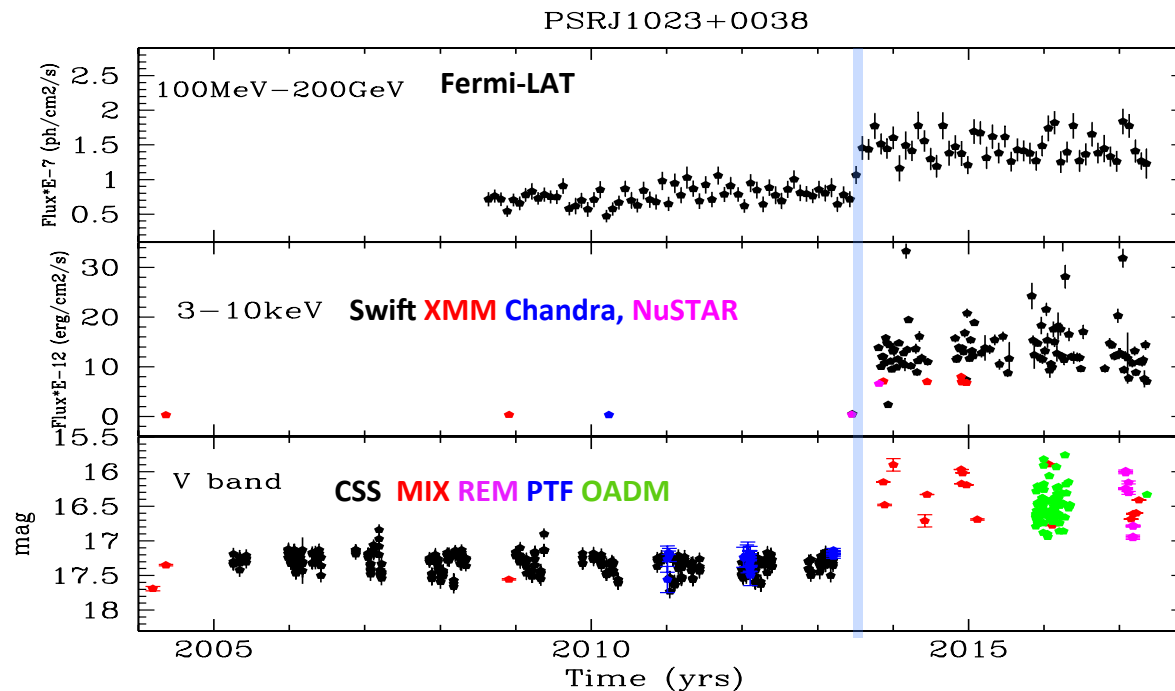
Ferrigno et al. 2014

PSR J1023+0038: a new state transition in 2013

RMSP



LMXB



RMSP OFF

$$L_{\gamma} \approx 0.1 \rightarrow 1.2 \times 10^{34} \text{ erg/s}$$

$$L_{\text{X}} \approx 0.5 \rightarrow 6 \times 10^{33} \text{ erg/s}$$

$$V_{\text{Opt}} \approx 17.5 \rightarrow 16.2 \text{ mag}$$

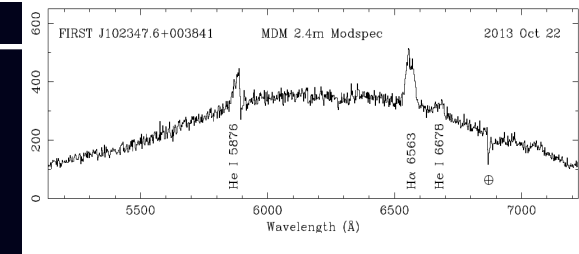
Accretion Disc

2004

Stappers et al. 2014
Tendulkar et al. 2014
Patruno et al. 2014
Bogdanov et al. 2015

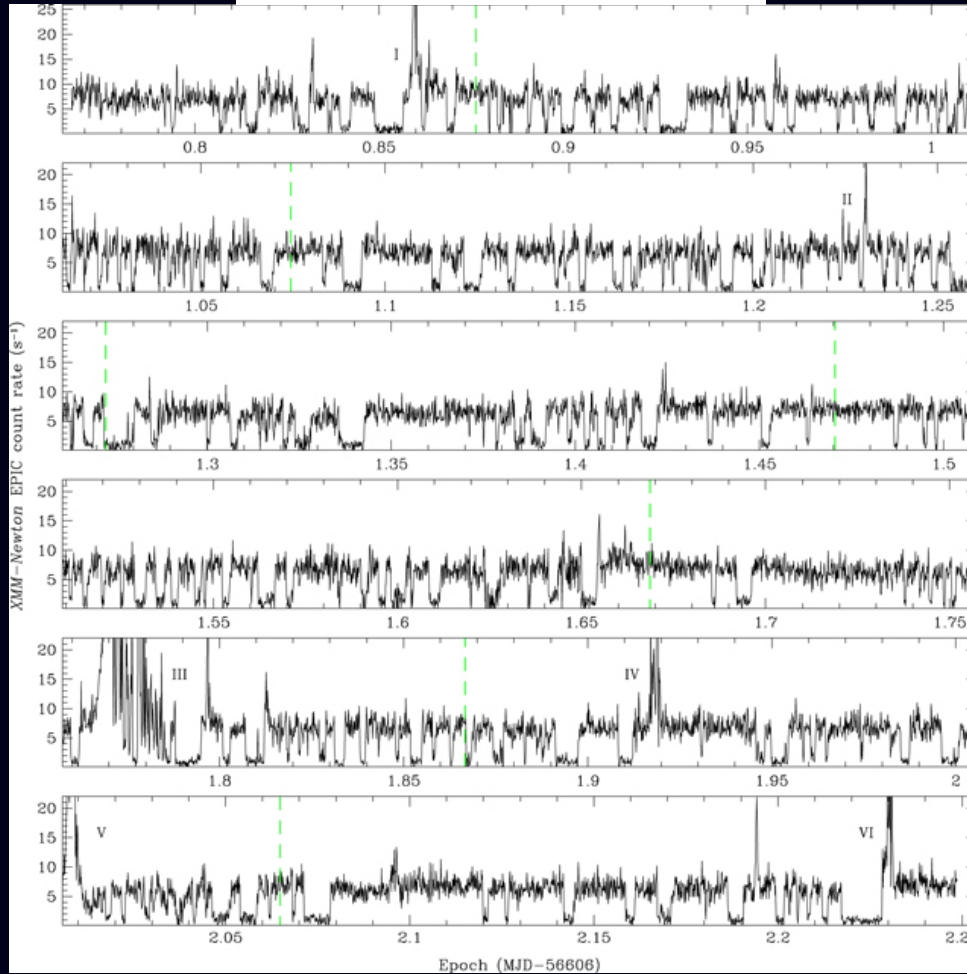
mid 2013

2017



PSR J1023+0038: the LMXB state

XMM-Newton Nov.2013



X-ray Tri-modal behaviour:

Erratic Flares $\approx$ tens mins up to 10hr

Erratic Dips = Low Mode $\approx$ secs-mins

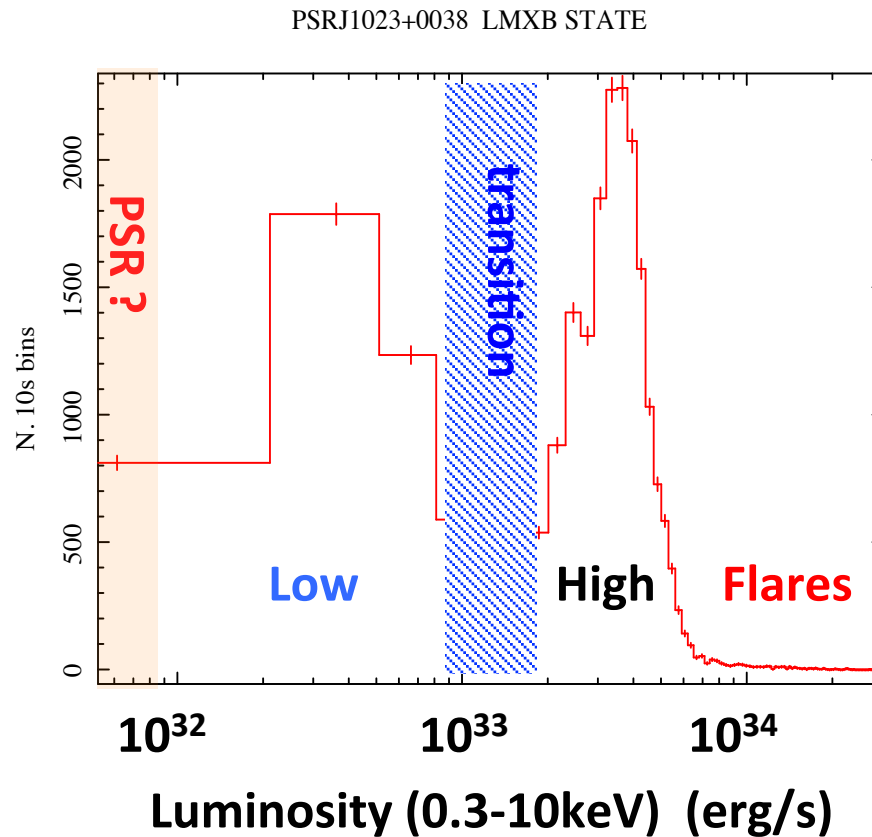
Persistent level = High Mode

Tendulkar et al. 2014

Bogdanov et al. 2015

PSR J1023+0038: the LMXB state

XMM-Newton 2013-2014

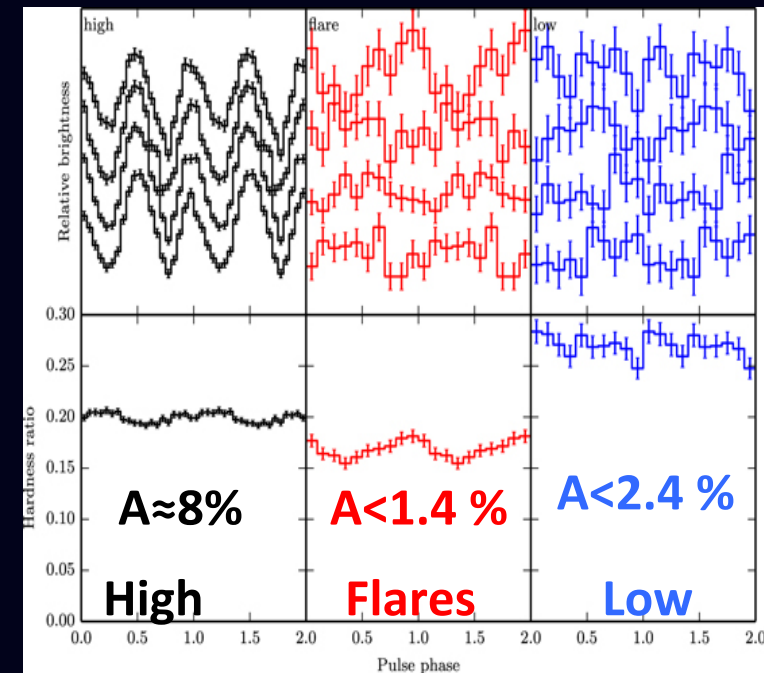


Bogdanov et al. 2015

Archibald et al. 2015

Mode switching in a few sec

X-ray pulses in high mode only



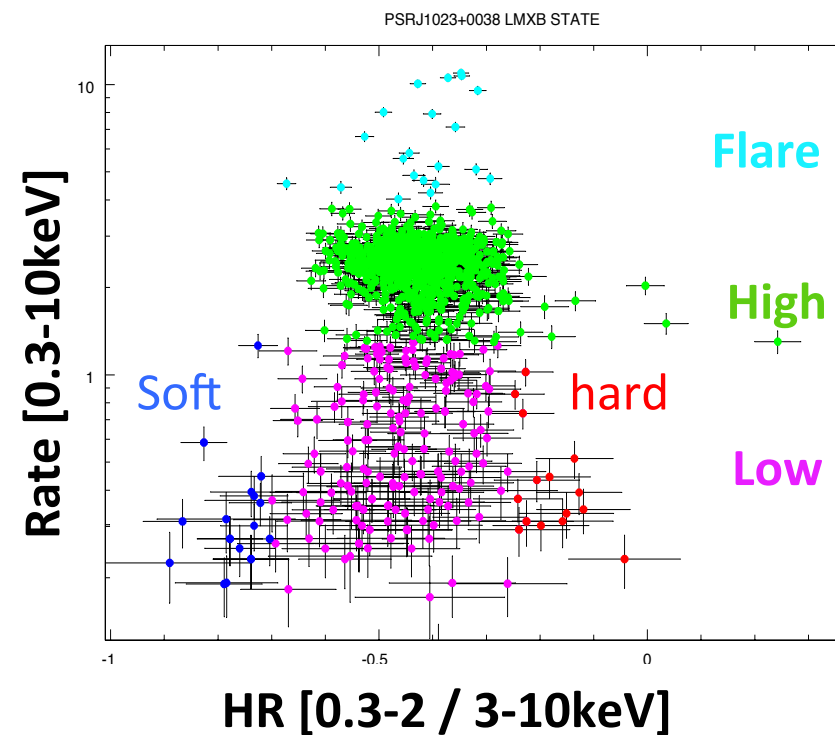
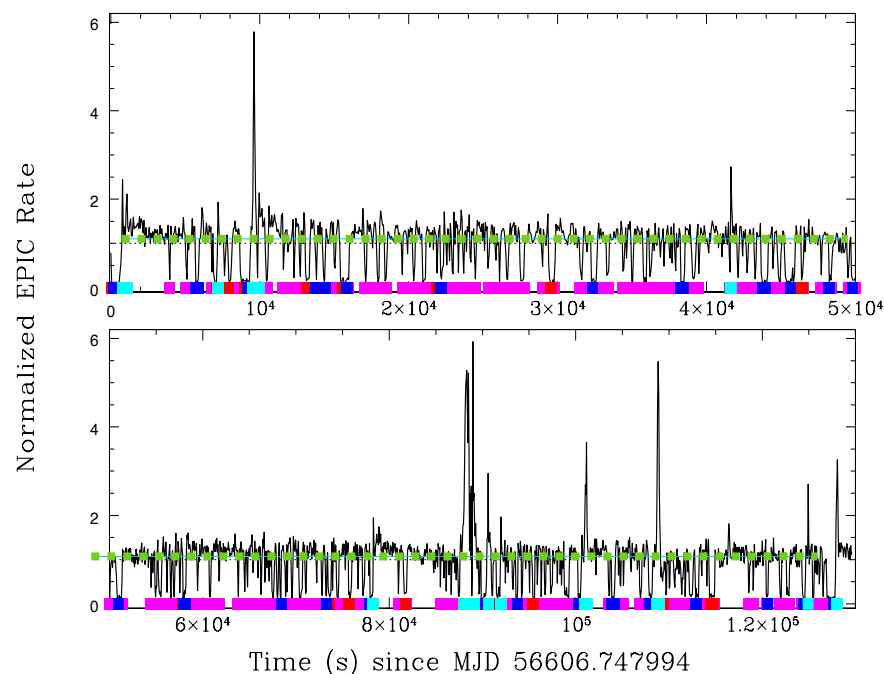
PSR J1023+0038: the LMXB state

No substantial spectral variability

but Soft & hard dips $\rightarrow$ subtle changes

XMM-Newton

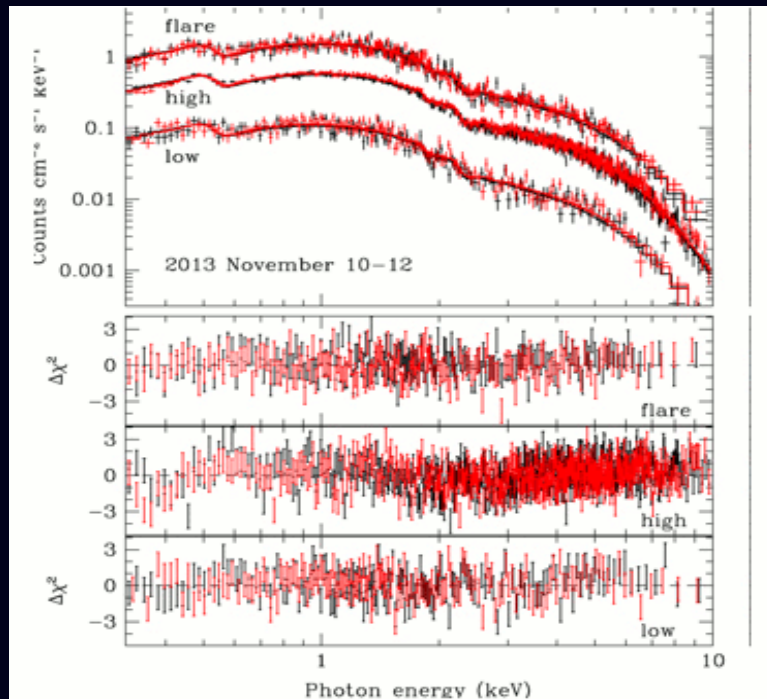
PSRJ1023+0038 LMXB STATE



PSR J1023+0038: the LMXB state

Average spectrum featureless : $\Gamma = 1.7$ softer than RMSP state $\Gamma = 1.26$

No substantial spectral variability - No thermal component



Flare: $\Gamma \approx 1.7$

High: $\Gamma \approx 1.7$

Low: $\Gamma \approx 1.8$

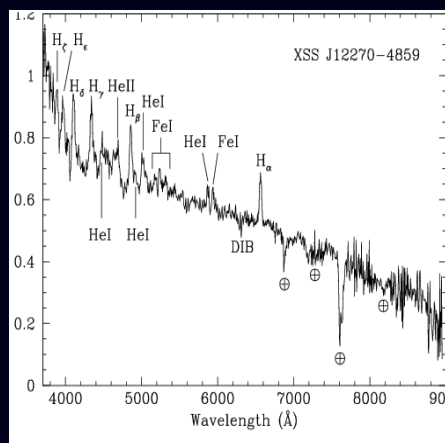
Dominated by outflowing matter ?

Bogdanov et al. 2015

XSS J1227-4859: a peculiar hard low-luminosity source

CV-like optical spectrum!

Variable Hard X-rays



Masetti et al. 2006

Sazonov & Revnivitsev 2008

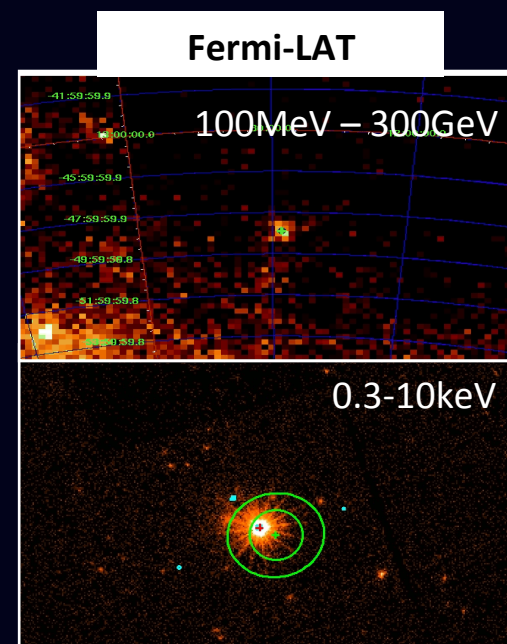
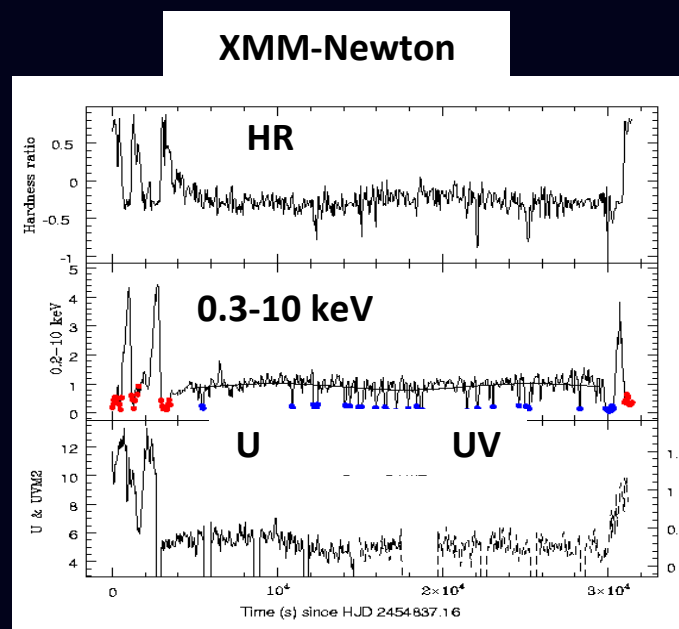
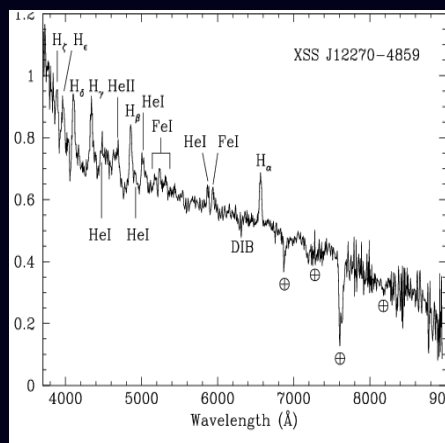
XSS J1227-4859: a peculiar hard low-luminosity source

CV-like optical spectrum!

Erratic X-ray - UV/optical variability

Fermi-LAT/XMM-Newton association

Variable Hard X-rays



2006

2007

2009

2010

Masetti et al. 2006

Sazonov & Revnivtsev 2008

de Martino et al. 2010

time (yrs)

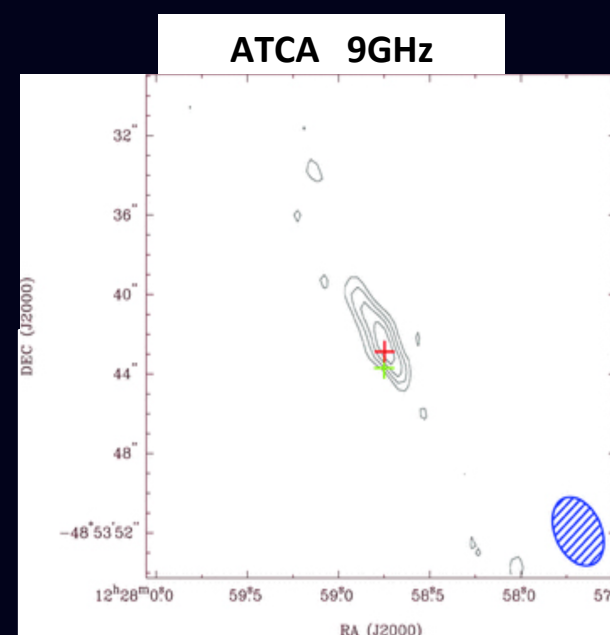
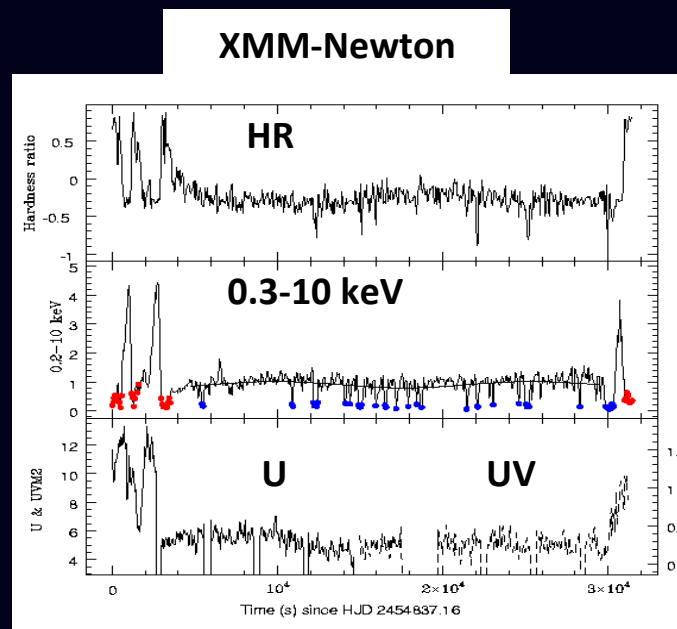
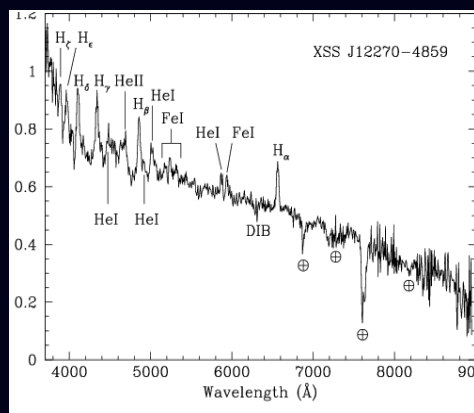
XSS J1227-4859: a peculiar hard low-luminosity source

CV-like optical spectrum!

Variable Hard X-rays

Erratic X-ray - UV/optical variability

Weak radio source



2006

2007

2009

2010

de Martino et al. 2010, 2013

Saitou et al. 2010

Hill et al. 2011

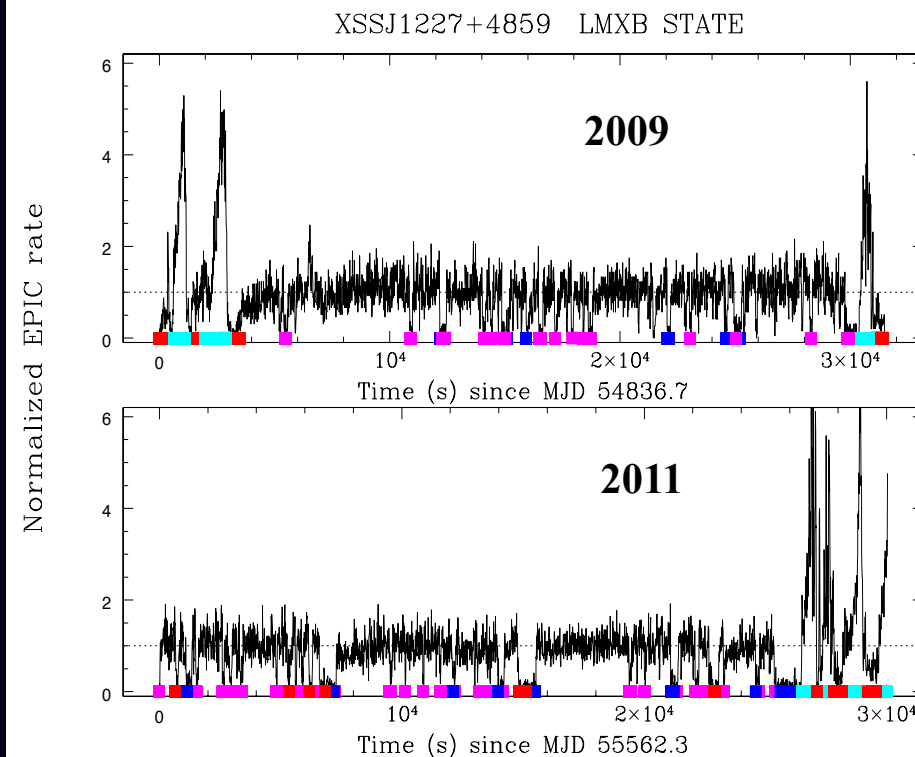
time (yrs)

Masetti et al. 2006

Sazonov & Revnivtsev 2008

XSS J1227-4859: the LMXB state

XMM-Newton



Tri-modal behaviour:

Sporadic Flares $\approx$ mins

Erratic Dips = Low Mode $\approx$ secs-mins

Persistent level = High Mode

de Martino et al. 2010,2013

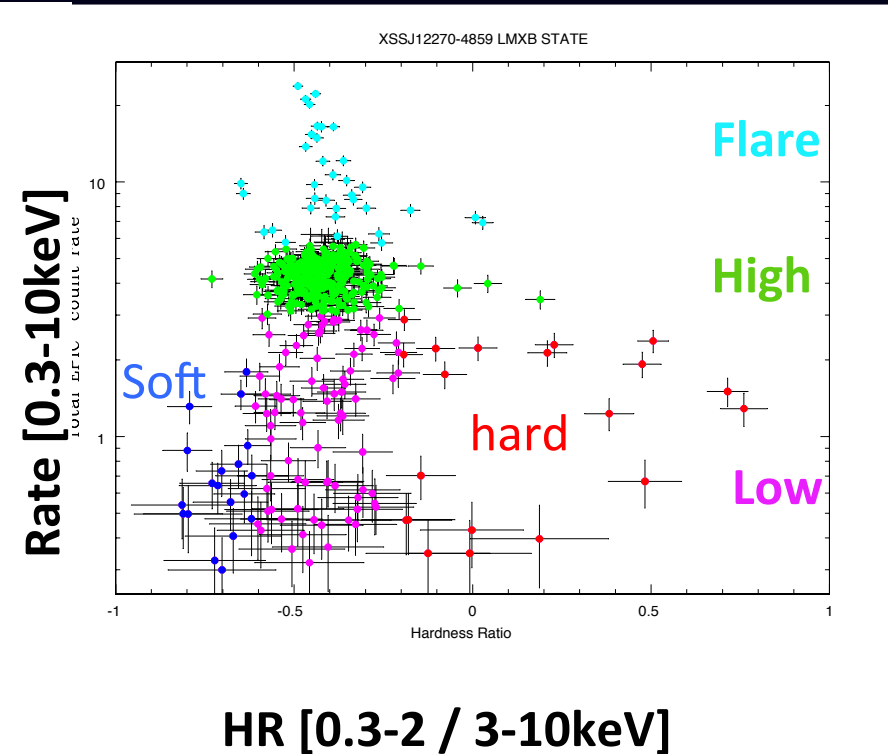
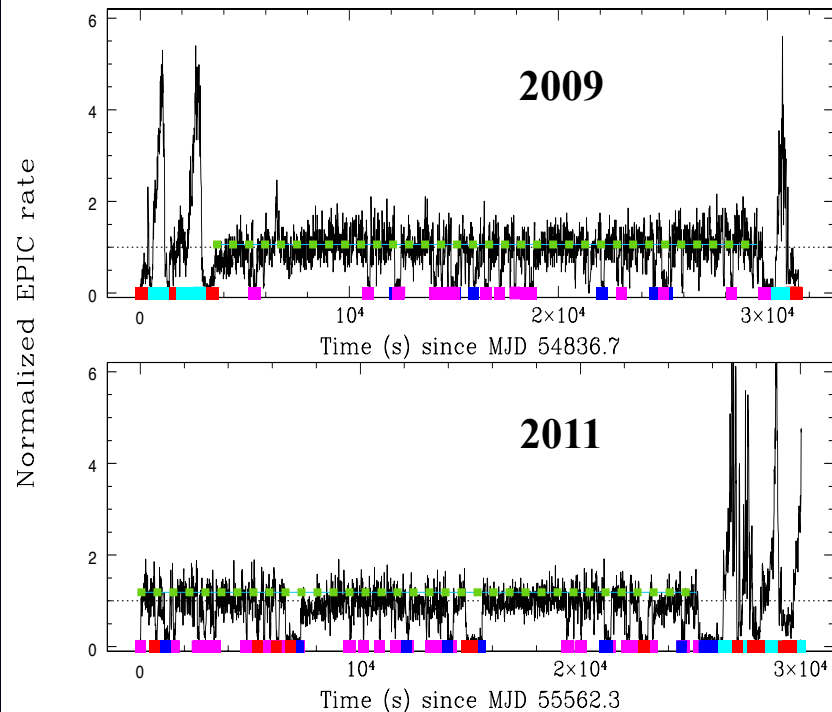
XSS J1227-4859: the LMXB state

No substantial spectral variability

but Soft & hard dips $\rightarrow$ subtle changes

XMM-Newton

XSSJ1227+4859 LMXB STATE

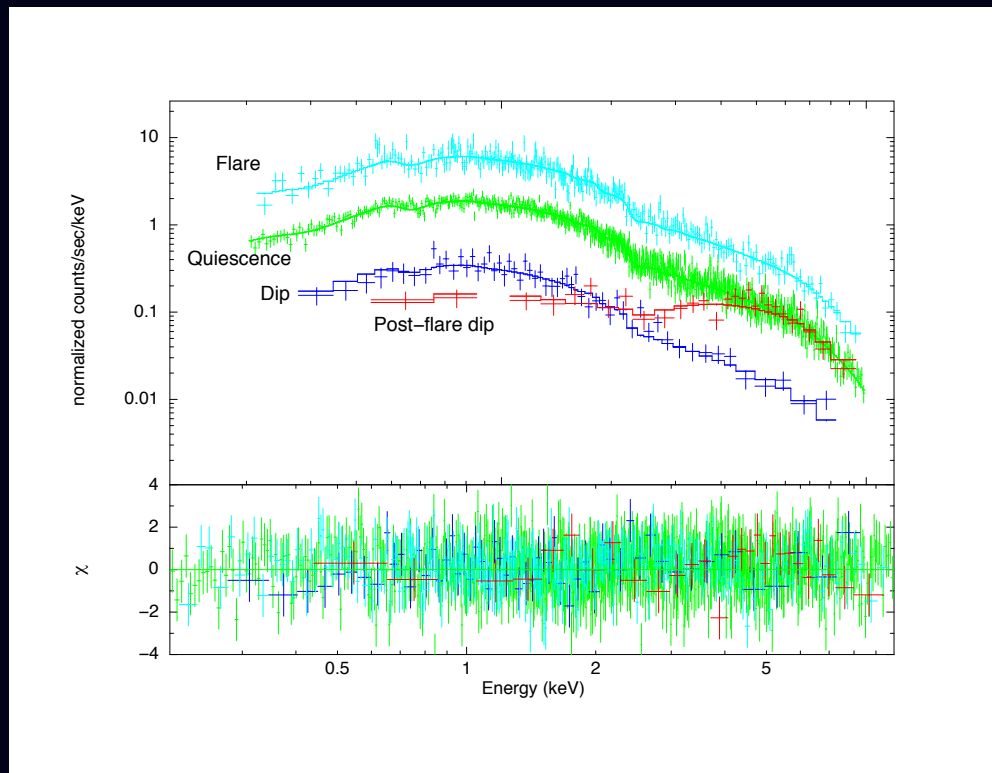


de Martino et al. 2010,2013

XSS J1227-4859: the LMXB state

Average spectrum featureless : $\Gamma = 1.7$

No substantial spectral variability except in Post-flare Dips



Flare: $\Gamma \approx 1.7$

High: $\Gamma \approx 1.6$

Dips: $\Gamma \approx 1.7$

Post-flare Dips : $\Gamma \approx 0.7$
+ PCF

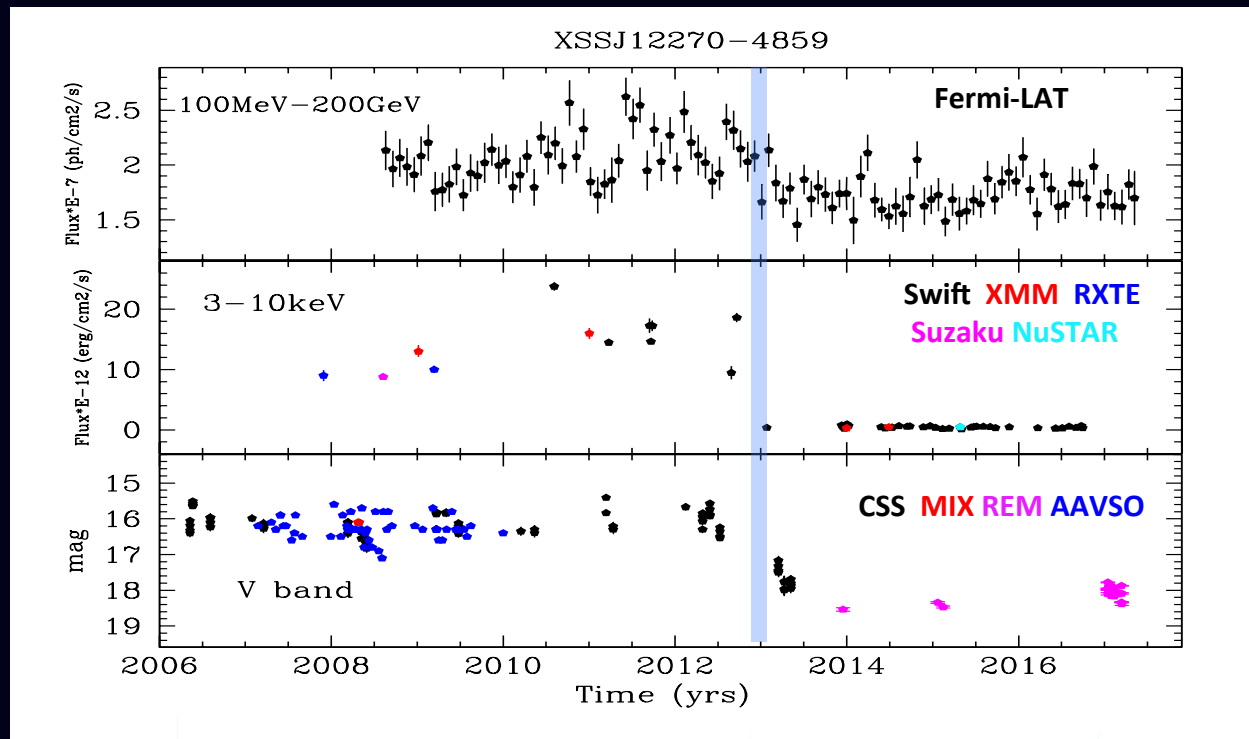
de Martino et al. 2010, 2013

XSS J1227-4859: a late recognised transitional MSP binary

Disc



Disc-free



$$L_{\gamma} \approx 1.1 \rightarrow 0.4 \times 10^{34} \text{ erg/s}$$

$$L_x \approx 6 \rightarrow 0.2 \times 10^{33} \text{ erg/s}$$

$$V_{\text{Opt}} \approx 16 \rightarrow 18 \text{ mag}$$

G-type optical spectrum

No disc

2006

Nov-2012- Mar.2013

2017

time (yrs)

Bassa et al. 2014

Bogdanov et al. 2014

de Martino et al. 2014

Torres et al. 2017

XSS J1227-4859: a late recognised transitional MSP binary

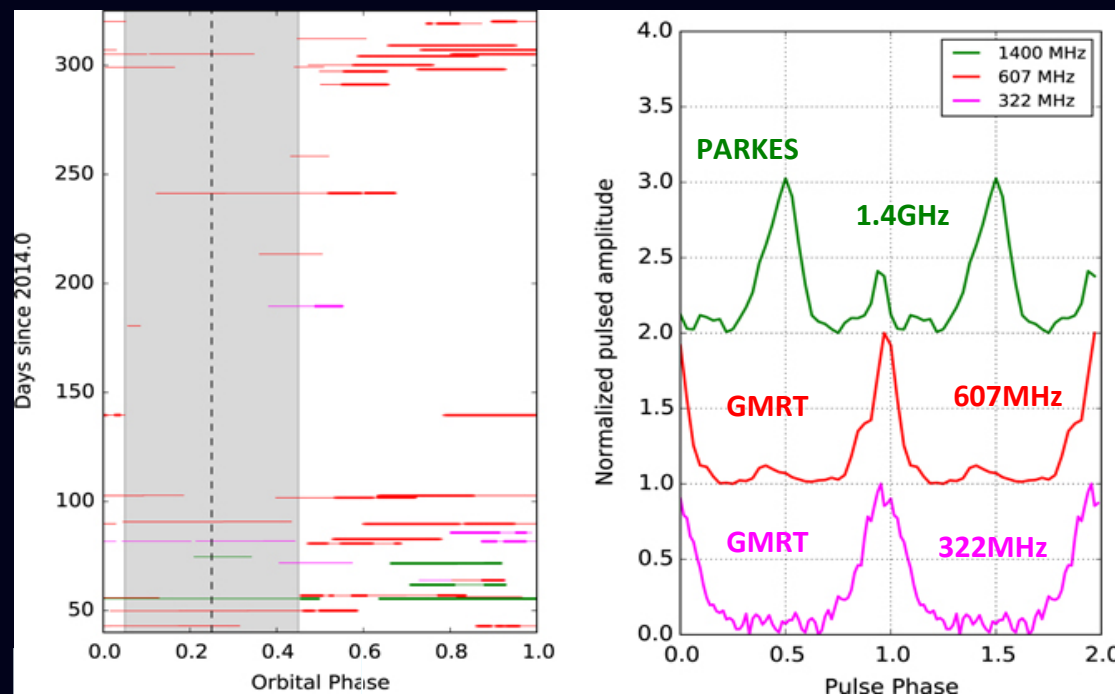
LMXB



RMSP

Radio Eclipses @ 6.91h

1.69ms Radio Pulsar



2006

Nov-2012- Mar.2013

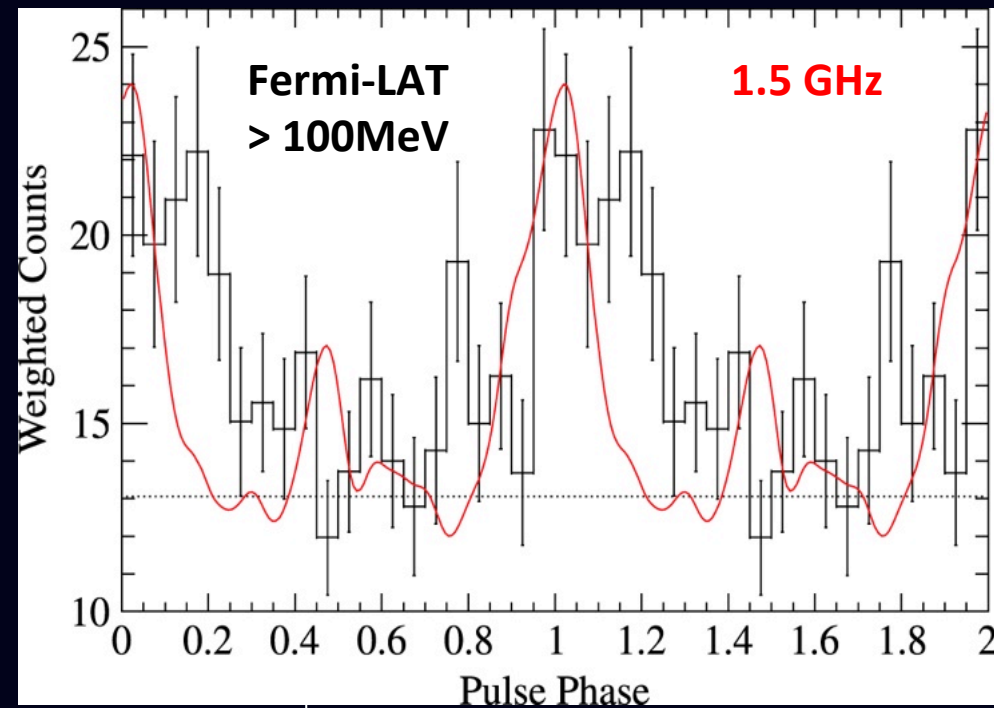
time (yrs)

Roy et al. 2015

XSS J1227-4859: a late recognised transitional MSP binary

LMXB  RMSP

Gamma-ray PSR @ 1.69ms



2006

Nov-2012- Mar.2013

time (yrs)

Roy et al. 2015

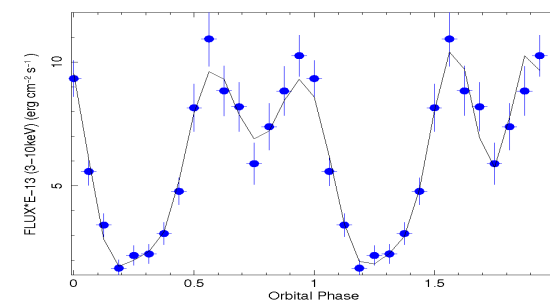
Johnson et al. 2015

XSS J1227-4859: now a Redback irradiated by Intrabinary Shock

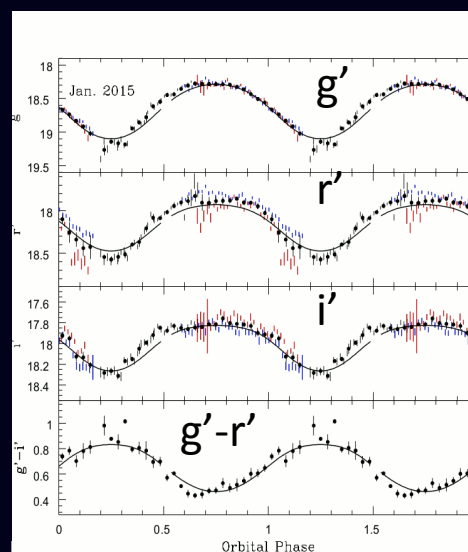
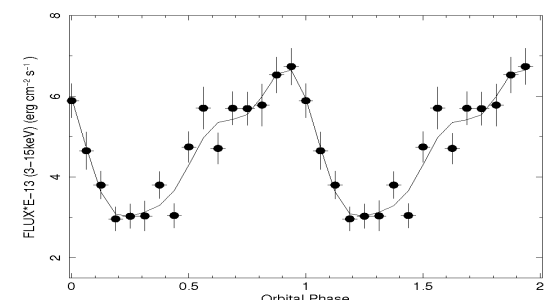
No X-ray Pulses @ 1.69ms
X-ray modulation @ 6.91h
Optical modulation @ 6.91h

XMM-Newton 0.3-12keV

XSSJ12270-4859 June 2014



NuSTAR 3-79 keV



2006

Nov-2012- Mar.2013

time (yrs)

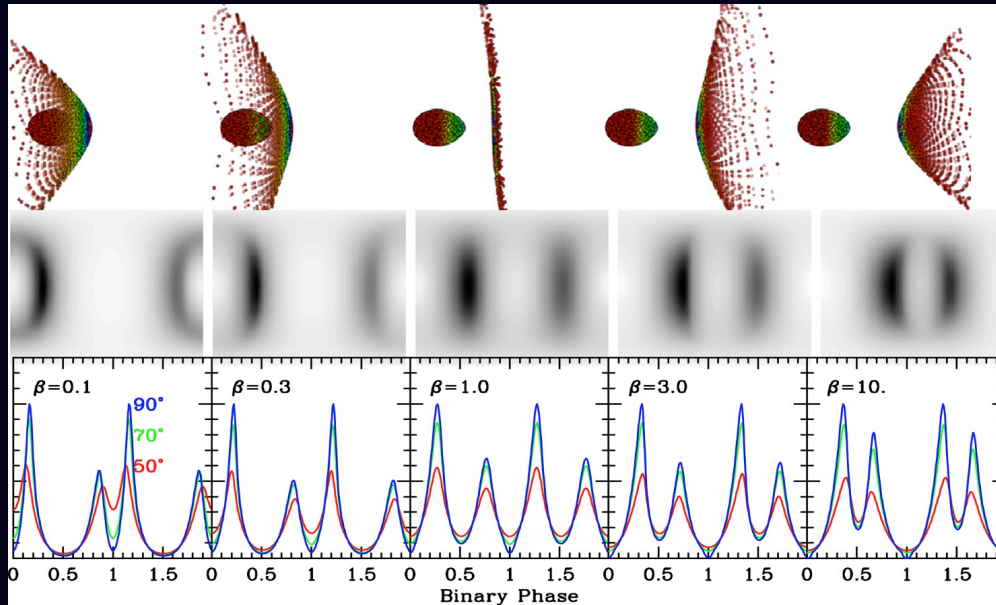
de Martino et al 2015

Papitto et al. 2015, 2017 inprep

XSS J1227-4859: now a Redback irradiated by Intrabinary Shock

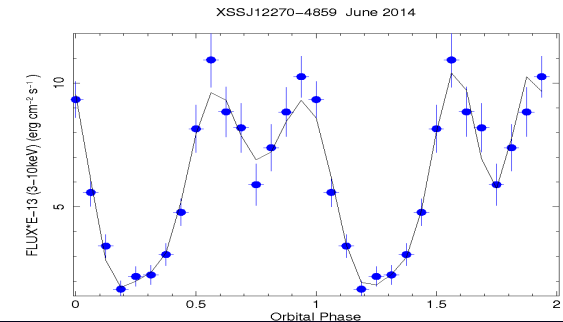
Intrabinary Shock dominates X-rays

Light Curve Shape depends on wind momentum ratio

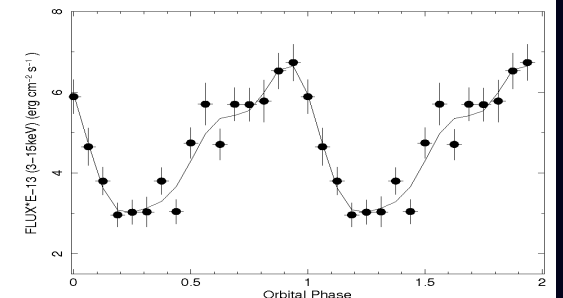


Romani & Sanchez 2016

XMM-Newton 0.3-12keV



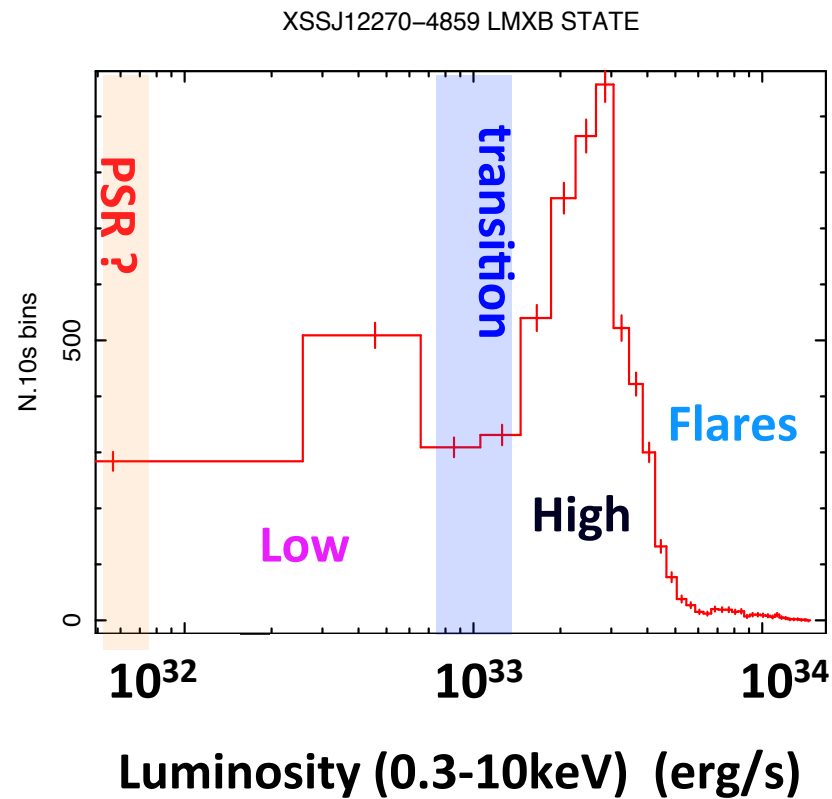
NuSTAR 3-79 keV



de Martino et al 2015
Papitto et al. 2015, 2017 inprep

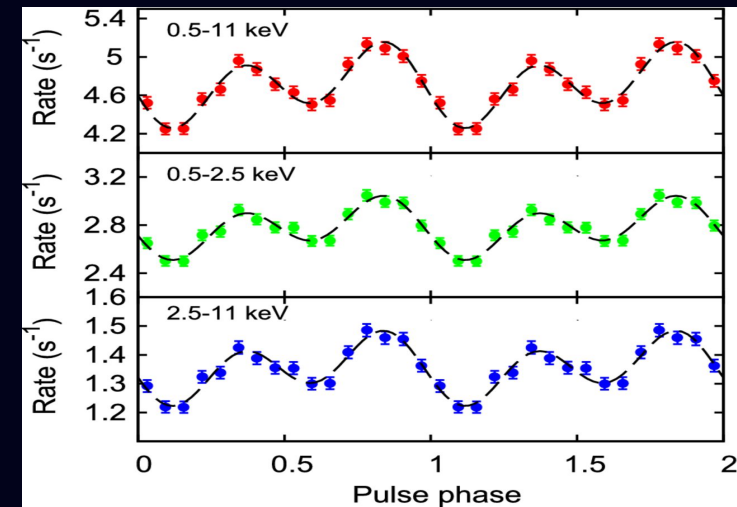
XSS J1227-4859: a late recognised transitional MSP binary

XMM-Newton 2009-2011



Mode switching

X-ray pulses in high mode only



$A \approx 8\%$	High	
$A < 2\%$	Flares	3σ
$A < 5.9\%$	Low	3σ

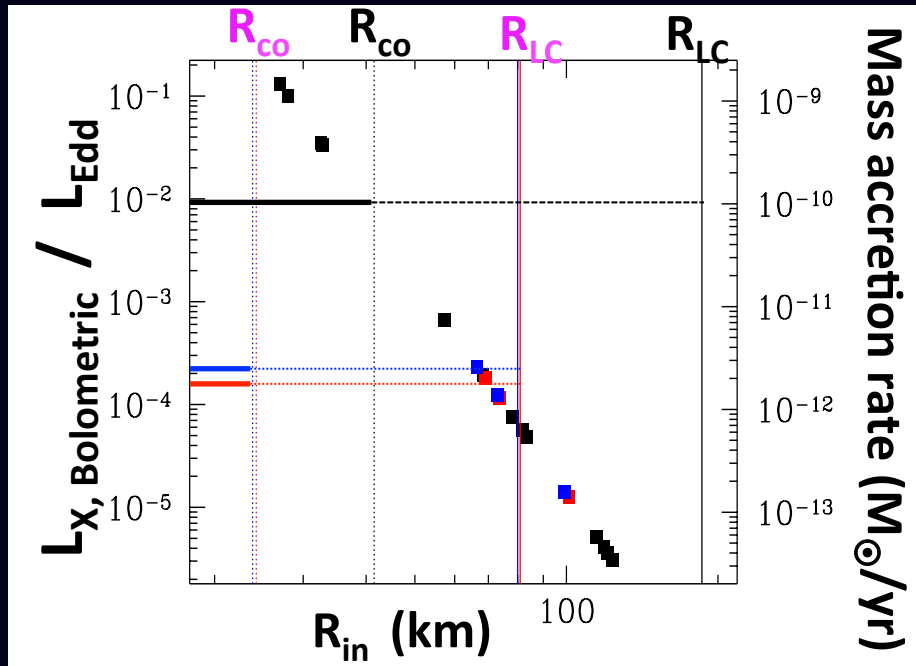
Papitto et al. 2015

Three states of tMSPs

M28I

PSRJ1023

XSSJ1227



- Mass inflow rate should be larger to have pulsations
- X-rays do not only trace the mass accretion rate on NS
- Advected energy in the disc powers propeller

[Listen Papitto – Binaries VI – Thurs. afternoon]

$$R_{in} \approx R_{mag} \propto M_{acc}^{-2/7} \mu_B^{4/7}$$

$$R_{in} \leq R_{co} \leq R_{LC}$$

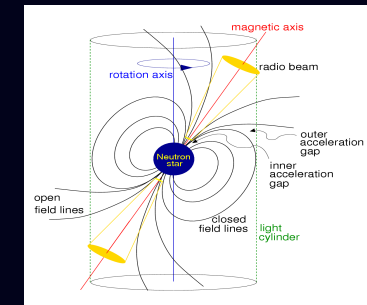
Accretion state

$$R_{co} < R_{in} < R_{LC}$$

**Accretion inhibited
Subluminous state**

$$R_{in} > R_{LC}$$

Radio Pulsar state



Linares 2014

Campana et al. 1998

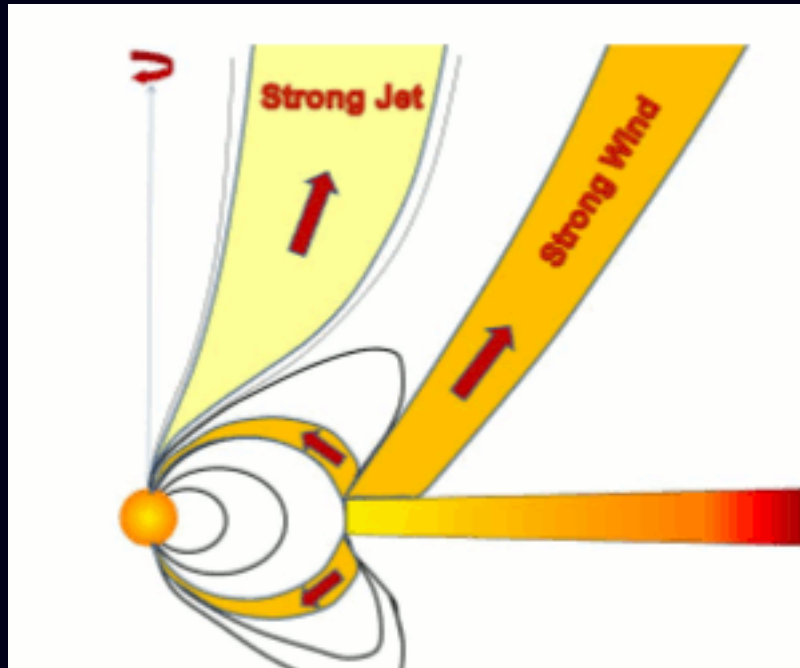
Romanova et al. 2014,2017

Papitto & Torres 2014,2015

Outflows in tMSPs

3-D MHD - Propeller driven winds & Jets

Romanova et al. 2014,2017



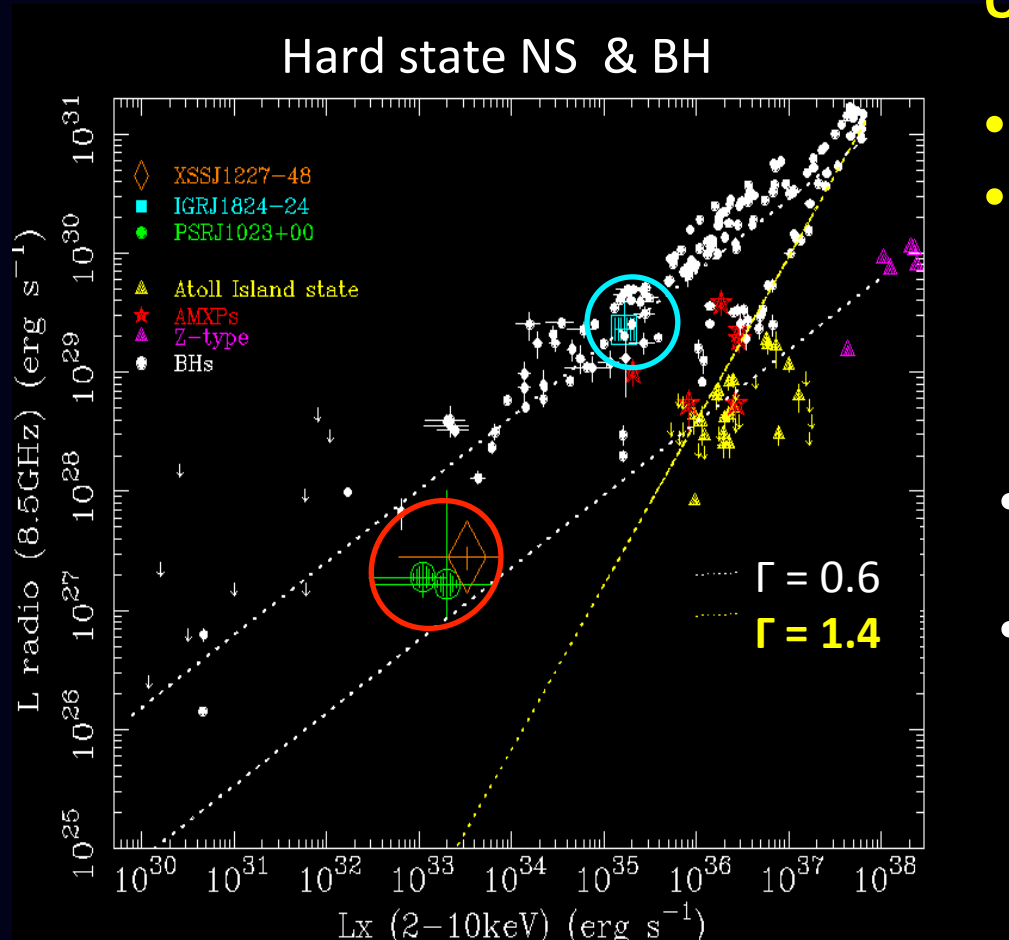
Strong propeller: $\omega_s = \Omega_{\star} / \Omega_k \gg 1$

2 Component Outflow

- Slow dense conical wind
- Low-density high-velocity jet

Accretion onto NS still possible

Outflows in tMSP



Observational Evidence ?

- Radio **variability** (mins)
 - Radio **flat-inverted** slope:
 $S_\nu \approx \nu^\alpha$ $\alpha \approx -0.05$

Hill et al. 2011
 Ferrigno et al. 2014
 Deller et al. 2015
 - tMSPs closer to BH than NS
 - tMSPs radio louder than other NS
- **Compact jet in tMSPs likely**

Few simultaneous X-ray & Radio obs

Longer simultaneous coverage needed!

BH, **Atoll**, **Z-type**, **AMXPs**, NS: from Migliari & Fender 2006, 2011 Gallo et al. 2014, Miller-Jones et al. 2010; Coriat et al. 2011+ref. therein

PSRJ1023: from Deller et al. 2015, **XSS1227**: from de Martino et al. 2015,

IGR1824: from Ferrigno et al. 2014

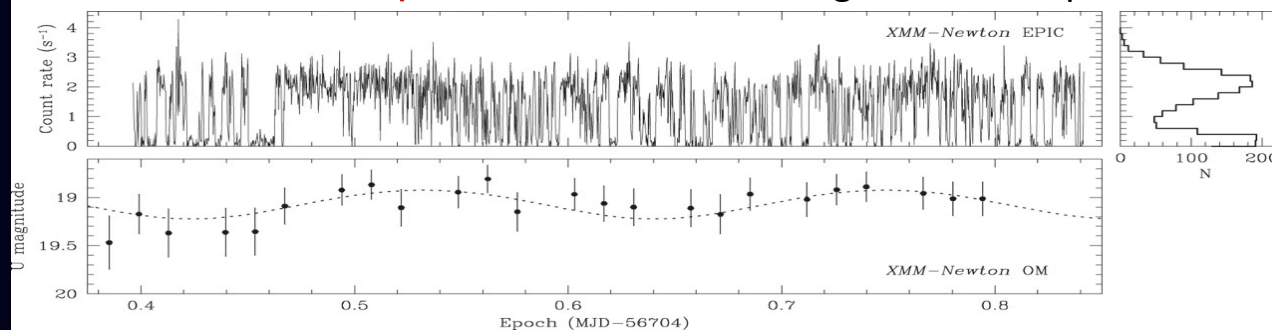
tMSPs: an intermediate or atypical evolutionary stage?

Need to find more !

Ongoing Intense Activities:

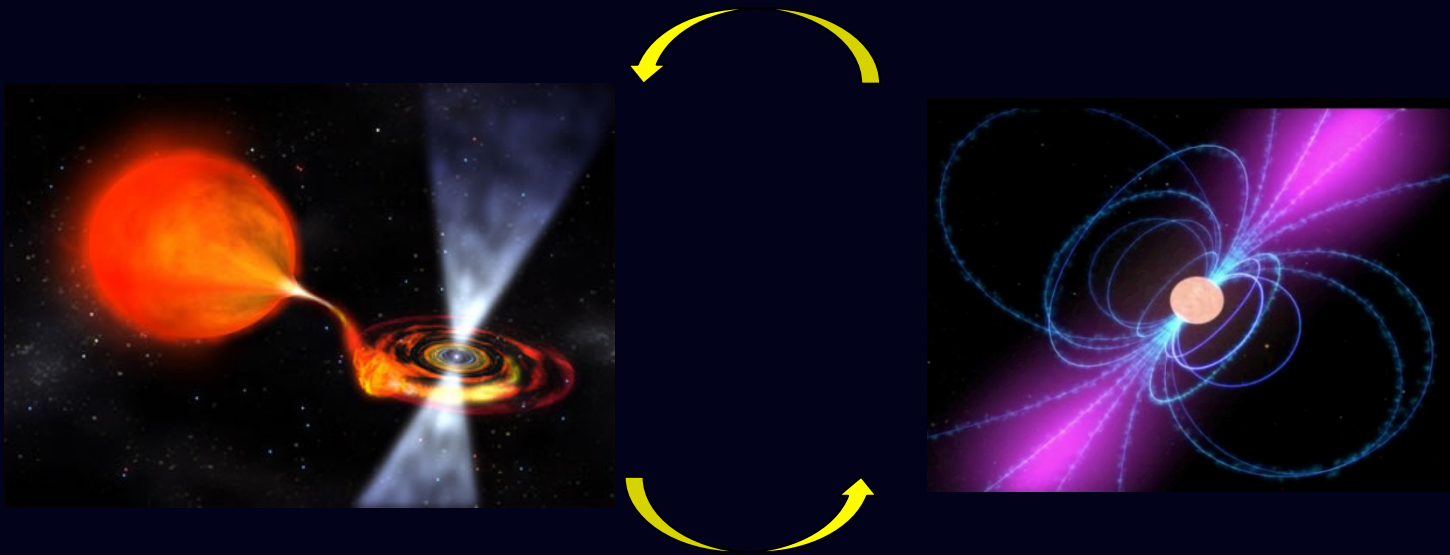
- X-ray, Radio & Optical search of counterparts of FERMI-LAT Unidentified sources
→ RBs, BWs and tMSPs candidates

3FGLJ1544-1128 / RXJ1544-1128 Bogdanov & Halpern 2015



- Long-term X-ray & Optical monitoring of known Radio Eclipsing RB
- X-ray deep observations of AMXPs in quiescence may reveal odd modes

Stay tuned!



Thanks:

T. Belloni, D. Buckley, M. Burgay, S. Campana, J. Casares, P. D'Avanzo, A. De Ona Wilhelmi, M. Falanga, C. Ferrigno, M. Linares, E. Mason, A. Possenti, D.F. Torres, N. Rea